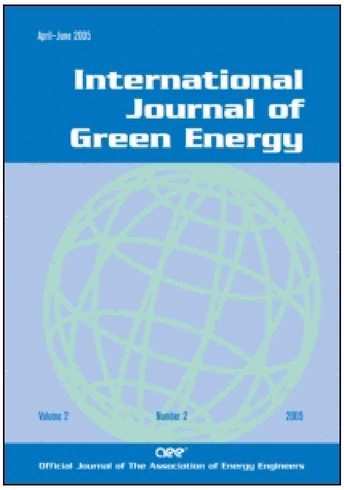

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A Holistic Method to Design an Optimized Energy Scenario and Quantitatively Evaluate Promising Technologies for Implementation

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A HOLISTIC METHOD TO DESIGN AN OPTIMIZED ENERGY SCENARIO AND QUANTITATIVELY EVALUATE PROMISING TECHNOLOGIES FOR IMPLEMENTATION

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In this article we focus on today's worldwide energy system, a fundamentally illogical and unsustainable system. Today, 85% of the world wide energy system depends on carbon-based fossil fuels. We develop a holistic method to analyze mankind's use of energy in a broad way and to design optimized, normative energy scenarios that conform to important scientific principles. The procedure is based on an abstraction process and helps to overcome thinking barriers and prejudice. The proposed method is applied to a general analysis of energy and to a simplified normative energy scenario for the United States in 2060. Important technologies for the implementation are evaluated in a bottom-up analysis. Since research endeavors and policies affect free-market decisions within the energy system, the developed method aims at guiding researchers and politicians to embark on strategies toward sustainable and scientifically optimized energy concepts for the future.

Keywords: ***Energy system analysis; Normative scenario technique; Bottom-up analysis***

INTRODUCTION

The current worldwide energy system[1] depends to a large extent (about 85%) on carbon-based fossil fuels (Tester et al. 2005), which provide the least expensive and most convenient options for energy conversion into useful applications. However, these resources are limited and are environmentally unsustainable. Converting the current fossil fuel based energy economies into sustainable systems presents a great challenge, but climate change and energy market forces are major driving factors. For a successful change, efforts in policy, technology, finance, and public acceptance have to be aligned. The currently observed sense of urgency is much influenced by impending consequences in global climate change, but the uncertainty of climate change policy (Yang et al. 2008) leads utility companies to delay new plant decisions. Power plants, expected to be built in the

[1] The expression energy system is defined in this article as a set of interacting energy conversion- and application components. An important characterization is the total input-/output quantity beyond its boundaries. The boundaries can encompass one component (e.g. power plant, car, etc.) up to a worldwide consideration of the sum of all components.

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next two decades, will comprise about 50% of the total generation capacity by the end of that period (Lior 2008). In addition, a number of new technologies are emerging, but they have not yet proven to be profitable. The choice of the design of the future energy system is now wide open but will be much narrower by 2020 (Goldemberg 2001). These circumstances, that is, uncertainty in policy, uncertainty in promising technology, high demand for new energy system capacities, and the long-term obligations, lead to major challenges in decision-making for future energy systems.

A historical analysis of energy system developments shows how energy sources and technologies have been consistently enhanced by innovations. In the late 1970s, Marchetti (1977) demonstrated that primary energy sources exhibited long-term trends. In his analysis, based on an extension of the Fisher-Pry substitution model, he used logistic curves to fit trends in the world's primary energy supply. The historically observed shifts in energy sources from wood to coal, oil, natural gas, and nuclear were extended recently to also include the current trend of energy efficiency and a future trend of renewable energy sources (Devezas et al. 2008).

Recent works by Tester et al. (2005) and Lior (2008) give an overview of energy sources and their use and of technologies that might be an integral part of the paths to the future. In general, there is a broad agreement that no single solution will solve the problems of high energy demand and minimizing detrimental environmental consequences (Whitesides and Crabtree 2007).

To explore future developments, the application of scenarios has gained much popularity, especially in energy and climate change research (Bunn and Salo 1993). The scenarios, in simple terms, are conjectures about what could happen in the future based on the past and present experience of the world. The literature distinguishes different types of scenarios (Hall 1987; Schwartz 1991; Virdis 2003), which include (a) extrapolatory approaches, assuming that the future is essentially defined as an extrapolation of the past; (b) normative scenarios, designed on a basis of a set of desirable features that the future world should possess; and (c) exploratory scenarios, which aim to explore several plausible future configurations of the world, giving perspectives on what might happen in the future. Most scenario forecasts on energy and sustainability are based on the exploratory approach (e.g. Ghanadan and Koomey 2005; Hall 1987; Martinot et al. 2007; Nakicenovic and Swart 2004; Shell 2008; Virdis 2003) incorporating possible changes in policy, economics, population, and technology. The scenario reports on the future of energy systems by the International Energy Agency (Virdis 2003) or Shell (2008) are extensive and represent a spectrum of possible paths considering a range of different developments.

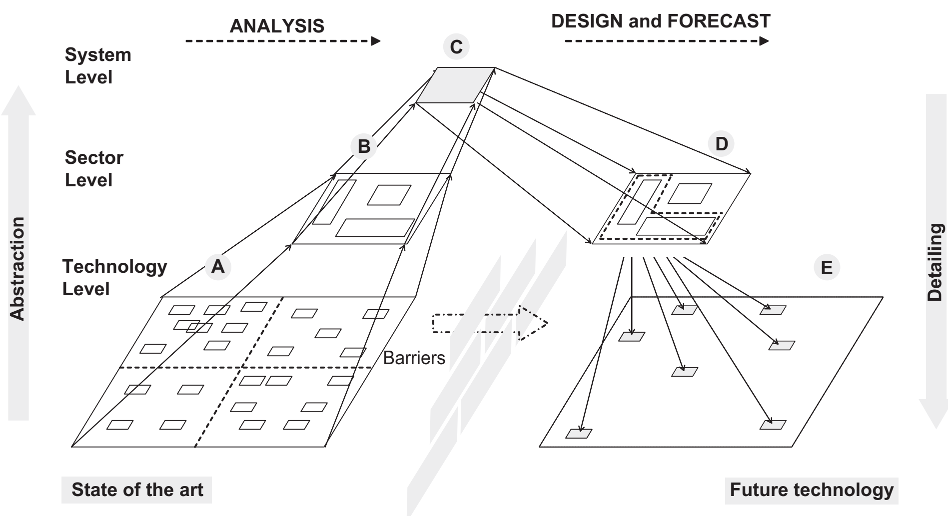
In this article we develop a holistic method to design future energy systems that conform to important scientific principles and the laws of sustainability. An abstraction process helps to analyze the present energy system and reveals key features that a future system should possess. The normative scenario is subsequently designed around these features. The proposed method differs fundamentally from widely used extrapolatory and exploratory approaches. Our method uses normative techniques to help decide what optimized future systems should look like. The IEA (Virdis 2003) states, ''How the future unfolds is to some extent determined by the actions we decide to take.'' Hence we want to give in this article a proposal how to design a logical future energy scenario and how to evaluate what has to be achieved to enable an implementation.

We give a quantitative but simplified example of an energy scenario for the United States in 2060. In addition, our bottom-up analysis of possible renewable but also fossil fuel based energy supplies shows the current state-of-the-art in conversion technologies, projects for the future, and sets benchmarks for research and development of renewable energy technologies to achieve economic competitiveness.

For a successful implementation of the designed future energy system, researchers have to achieve the benchmarks given by market forces but on their way must also be supported by adequate legislation.

METHODOLOGY

With the objective of seeking a desirable energy system and identifying appropriate technologies, a method has been developed to systematically analyze the broad field of energy and to generate an optimized and quantitative scenario of future energy supply and conversion technologies. Figure 1 schematically shows this method including its sections A to E. In contrast to well-established exploratory scenario techniques for future energy paths (Ghanadan and Koomey 2005; Hall 1987; Martinot et al. 2007; Nakicenovic and Swart 2004; Virdis 2003), the developed method is primarily based on the normative



A) Situation analysis on energy technology
- Investigation of the state of the art
- Research on emerging technologies
- Expert interviews
- Opinions revealed at conferences

B) Compressing and structuring analysis results
- Creation of subsystems
- Mind mapping
- Strength and weakness analysis

C) Problem abstraction
- Analysis of cause and impact
- Abstraction of the energy system as a whole
- Revelation of system analysis insights
- Determination of key features that future energy scenarios should possess

D) Normative scenario prognosis
- Key features serve as pillars
- Choosing future energy sources
- Choosing future conversion technologies
- Quantitative energy scenario

E) Bottom-up analysis of potential implementation technologies
- Identification of drivers for change
- Interdependencies among drivers
- Quantitative prognosis of future potentials

Figure 1 Methodology for design and forecast of future energy systems.

scenario approach. The normative type creates future scenarios based on desirable features. The identification of these features requires an extensive knowledge of the broad energy sector.

However, to reach well-grounded decisions, thinking barriers and prejudice must not be present. The proposed system analysis method abstracting the energy field overcomes such possible obstacles and can be used to determine design features for optimized energy systems while observing scientific fundamentals.

Section A represents the situation analysis, which is followed in section B by structuring and compressing analysis results. The main result of the system analysis, section C in the flow chart, is a simplified overview of the present energy system and determines important features that have to be incorporated into a design for the future.

The generation of a normative energy scenario in section D is based on the analysis of the energy sector and the revealed key features for future energy systems. These features are considered when establishing an optimized path for energy supply and conversion technologies. Section E comprises a bottom-up prognosis on selected power generation technologies to show possible future potentials and to give useful insights for further development. The driving parameters, their interdependencies, and effects on electricity production costs become clear.

The scenario and analysis results are not an accurate forecast of the future but a desirable normative system design and should help decision makers in research, politics, and industry to choose effective options for future developments.

ABSTRACTION

Sections A and B in the developed system analysis (Figure 1) are the fundamental basis of the abstraction process and will not be discussed in this article. Based on a broad situation analysis of the energy field, the abstraction results (section C) will provide a condensed overview and lead to a logical energy concept.

3.1. System Analysis Insights

Energy as the leverage of human activity. In the first instance, living beings obtain energy to live from organic food. Human beings have developed further and have increased their standard of living by using external energy through the aid of technology to leverage their activities. In industrialized nations, the average energy consumption per person exceeds the minimum biological requirements by a factor of 56 (Spliethoff 2006), in the United States by the factor of 125 (Tester et al. 2005). Availability of energy has turned out to be an important factor for economic growth (Lee and Chang 2007).

Sustainability. Sustainability can be described as ‘‘a dynamic harmony between the equitable availability of energy-intensive goods and services to all people and the preservation of the Earth for future generations’’ (Tester et al. 2005). The current energy system is not sustainable for two reasons. First, the world’s energy consumption is 85% dependent on carbon-based fossil fuels, in the United States fossil and nuclear fuels account for 94% of primary energy consumption (Conti et al. 2008). Since these fuels are limited, this energy supply not sustainable. Second, the current energy system is a major contributor to the enhanced global climate change due to greenhouse gas emissions (Trenberth 2004). Changes in the ecosystem caused by climate change are hard to predict, but there is a broad consensus that the consequences will be extensive. To preserve a healthy ecosystem, it is suggested to limit the CO_2 concentration in the atmosphere to 550 ppm (2008: ~380 ppm) (Sokolov et al. 2004). The level of 550 ppm is predicted for the year 2050. Hence the decarbonization of the energy sector has to be addressed now.

Energy. Energy is an abstract physical value. Physicists define it as the amount of work a system is capable of performing. The first law of thermodynamics expresses the physical law that energy is conserved. Energy can only be converted from one source to another. In practice, each conversion process is associated with losses. The second law of thermodynamics defines each conversion step as irreversible due to dissipated work (e.g. friction) as a nonconvertible by-product, and the entropy of the system will increase.

The fundamental energy of mass goes back to Einstein's theory of special relativity (1905). The origin of all types of energy lies in Einstein's formula, according to which mass can be transformed into energy.

$$E = mc^2 \tag{1.1}$$

Energy sources. Approximately 14 billion years ago the universe most likely evolved out of the big bang (Steiger 2004). This is regarded to be the best available cosmological model of the universe supported by all lines of scientific evidence and observations. According to Einstein's relativity theory, the simplified explanation is that energy turned into mass and formed the planets during the formation of the universe (Eq. 1.1).

Today, all energy resources on Earth still have their ultimate roots in relics of the big bang. The fusion process in the sun is continuously converting mass back into energy. Energy resources given by geothermal heat and planetary motions are still available through the original formation of the galaxy. Fossil fuels conserved in the Earth's crust were created by solar energy and biological processes over millions of years. Figure 2 shows the origin of energy sources on Earth.

In terms of energy sources, the Earth can be regarded in two ways. It can be seen as a closed thermodynamic system with the atmosphere as its boundary. In this case the available energy resources are fossil fuels such as oil, gas, coal, uranium, and geothermal energy. These can be used in several applications but, except for geothermal energy, are finite sources. The present high dependency on fossil fuels renders the current energy

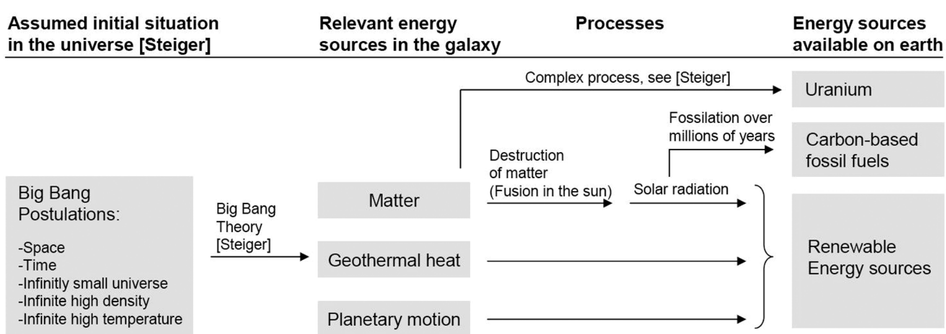


Figure 2 Origin of energy sources.

situation nonsustainable. Table 1a shows the resources to production-ratio (R/P) of major fuels. This ratio reflects how long current mining activities can be adhered to at a constant production rate assuming no additional resource discoveries.

The planet Earth is not a closed thermodynamic system. It receives electromagnetic radiation from the sun and emits radiation of mainly high wavelengths (heat) into the

Table 1 Energy sources and energy demand.

	R/P-Ratio	Unit	Source
a) Finite energy sources			
Oil	41.6	a	(BP p.l.c. 2008)
Coal	133.0	a	(BP p.l.c. 2008)
Natural gas	60.3	a	(BP p.l.c. 2008)
Uranium	78.5	a	(Zittel and Schindler 2006)
	Flows or Stores	Unit	Source
b) Renewable energy sources			
Solar energy	3,850	ZJ/a	(Smil 2005)
Wind	2	ZJ/a	(Archer and Jacobsen 2005)
Biomass	3	ZJ/a	(FAOUN 2008)
Geothermal	13,000	ZJ (total)	(Tester et al. 2006)
	Amount	Unit	Source
c) Energy consumption			
Worldwide	0.487	ZJ/a	(Energy Information Administration 2007)

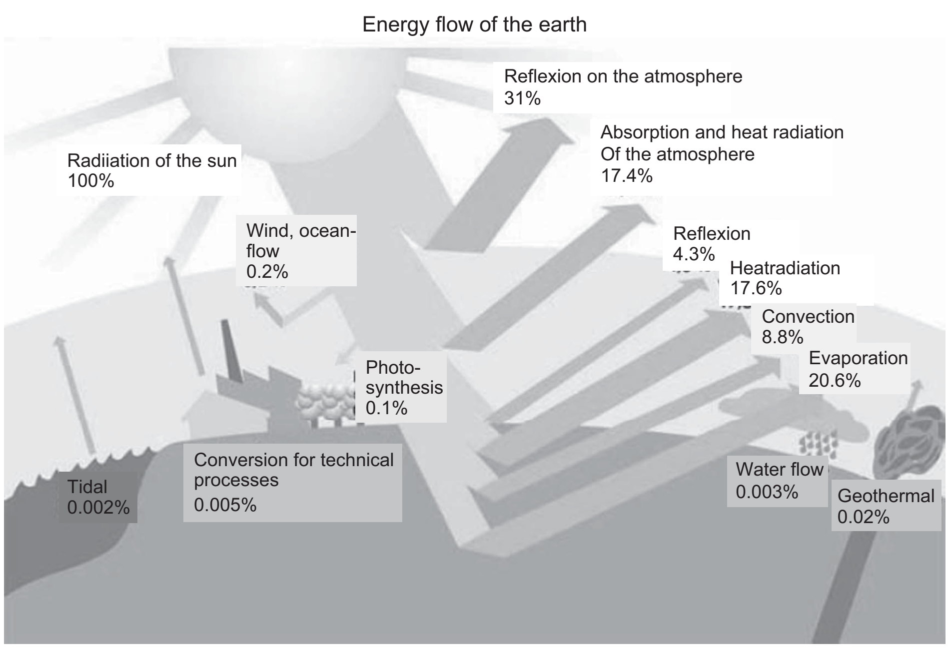


Figure 3 Energy flow of the earth, adapted from Spinnler and Blumenberg (2007).

universe, shown in Figure 3. The Earth is therefore energetically embedded into the galaxy and operates as an open thermodynamic system by exchanging energy across its borders. The Earth's energy absorption and radiation processes, enhanced by the rotational motion and gravitational forces of other planets, affect the climate, which in turn results into renewable energy sources such as solar, biomass, wind, hydro, wave, and tidal energy. Table 1b summarizes these sources and indicates their sustainability with respect to worldwide energy consumption which is shown in Table 1c.

Energy usage. Energy can be used to power a variety of devices such as cars, heating systems, and lamps, or it can be used in the production of industrial products. These goods and services all improve living standards. Energy consumption per person is low in developing countries and high in developed countries. Table 2 shows energy consumption per capita for different economic regions.

Depending on the geographical location and economic wealth, energy is used differently. For industrialized nations, the main energy consumption segmentation is shown in Table 3. Heat in buildings and for industrial processes takes the major share, followed by kinetic energy for transportation and electricity.

Energy conversion. Conversion of energy transforms primary energy sources into other energy types and finally into useful applications. To harness energy sources and to transform the energy for use in applications, technical devices are necessary. The composition of the energy source plays an important role in the practicability of the various possible conversion processes, but the applied process technology is also an essential factor in using the energy source as effectively as possible.

3.2. Determination of Key Features

The abstraction process of the energy sector reveals important points for supplying energy-intensive goods and services in an optimized and sustainable way. It suggests six key features that future energy systems should possess.

Table 2 Energy consumption per capita, adapted from Spinnler and Blumenberg (2007).

	Developing countries	China, GUS-states	Europe	North America	Japan, Australia
Energy consumption per capita [GJ/year]	26	70	156	366	141

Table 3 Energy consumption segmentation for industrialized nations, adapted from Conti et al. (2008) and the U.S. Department of Energy (2007).

Domain		Energy type		Summary	
28%	Transportation	28%	Kinetic energy	28%	Kinetic Energy
39%	Buildings	15.7%	Electricity		
		23.3%	Heat	43%	Heat
33%	Industrial	13.3%	Electricity		
		19.7%	Heat	29%	Electricity
$\Sigma = 100\%$		$\Sigma = 100\%$		$\Sigma = 100\%$	

- **Consideration of Environmental Impact**
  The energy supply has to be sustainable in order to preserve the Earth for future generations. A worldwide agreement on financial sanctions for environmental pollution will shift the free market economy toward sustainability. The Kyoto protocol and an applied CO_2 cap and trade system are suitable approaches.
- **Utilization of renewable energy sources**
  The Earth has to be regarded as an open thermodynamic system, and the various renewable and hence inexhaustible energy sources need to be utilized.
- **Minimization and optimization of energy conversion**
  In each energy conversion process in practice, losses occur. Minimizing the number of conversion steps and optimizing the processes will result in a better energy balance. Direct conversion technologies, which are not restricted to the Carnot limitations, are pioneering in this context.
- **Using the optimal energy source for each application**
  Each selected energy source should be chosen to suit its final application. For example, for the biggest share of energy demand, heat, energy sources in such form should be used directly without performing conversion steps.
- **Choosing power plant types according to locally available energy sources**
  Power plant types should be selected after consideration of site conditions with respect to locally available energy sources. Local subsidies should not distort the free market conditions, which usually create most efficient systems.
- **Integral energy systems**
  The use of energy sources and conversion technologies for different applications should be planned as an integral energy system. The mutual support of partial elements in a holistic approach will result in the best possible energy balance. Combined heat and power technologies are an example of high overall fuel efficiency.

A FUTURE ENERGY SCENARIO

A future energy path is given using the normative scenario techniques (step D in Figure 1). The insights of the system analysis revealed six key features that will serve as pillars in the design of the system. It is assumed that consumption patterns and quantities would stay the same.

4.1. Choosing Future Energy Sources

The energy supply will shift from fossil fuels to renewable energy sources. Table 4 gives a comparison of current major energy sources with promising energy sources for the future according to the suggested features. Future sources will be matched to their applications and can be used optimally in conversion processes.

4.2. Choosing Future Conversion Technologies

Currently used energy conversion technologies are based around the use of heat. More than 90% [2] of worldwide energy sources are converted into heat.

[2] Worldwide fossil and nuclear fuel are almost completely converted into heat.

Table 4 Present and possible future energy sources.

	Currently used energy sources	Logical path for the future
Transportation	Crude oil	Biofuels Hydrogen or electricity from renewable energy sources
Heating buildings & heat for industrial processes	Natural gas Coal Crude oil Electricity Biomass	Geothermal heat Solar heat Biomass Low level heat from the environment (Heat-pumps using electricity from renewable energy sources)
Electricity	Coal Uranium Natural gas Hydro	Hydro Solar photovoltaic Solar thermal Wind Biomass Geothermal Waves, Tidal, Ocean thermal, etc. Matter (direct conversion via fuision)

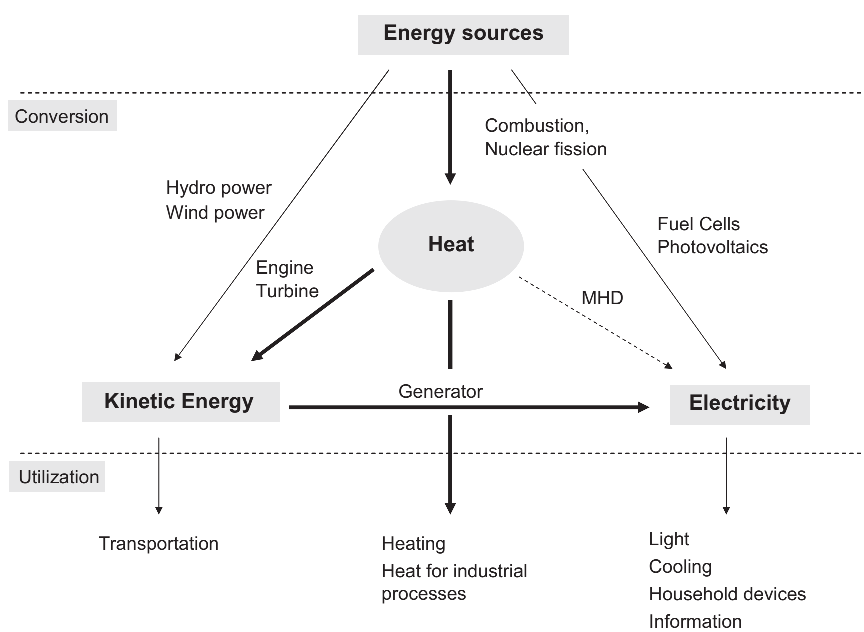


Figure 4 Schematic overview of energy conversion technologies, adapted from Spliethoff (2006).

The generated heat is either utilized directly or converted into kinetic energy. Applications for kinetic energy include transportation and electricity production via generators. Figure 4 shows the energy conversion steps. In the United States more than 90% of the generated electricity (Conti et al. 2008) and also the majority of transportation technologies are derived from heat used in an intermediate step in conversion processes, limited to Carnot's laws. New, direct, and potentially more efficient conversion technologies will displace processes based on combustion engines and steam and gas turbines. These technologies are not only more efficient, but they also enable the direct use of renewable energy sources.

In the transportation sector two major technologies, fuel cells and batteries, have great potential to substitute combustion engines. A drive train that uses batteries in combination with electric motors can offer a plug-to-wheel efficiency of 80%—90% (Tesla Motors Inc. 2008). Cars using fuel cells as energy conversion devices will reach a tank-to-wheel efficiency of approximately 50%[3]. But conventional cars using combustion engines have tank-to-wheel efficiencies of only approximately 20% (U.S. Dept. of Energy 2008).

In order to provide heat for industrial and residential use, the application of heat pumps, geothermal, solar, and waste heat will increase. Further conversion of heat is accompanied by high losses and hence should be avoided. Highly flexible energy sources and carriers (e.g. fuels, electricity) should rather be used in more challenging applications than for heating.

The future electricity generation will use the variety of renewable energy sources. The sun's energy should be converted using efficient photovoltaic cells. Renewable energy sources based on fluid flow, such as wind, hydro, wave, and tidal energies, will be harnessed using efficient turbines or new technological approaches.

A Quantitative Energy Scenario for the United States

The United States accounts for 21% of worldwide primary energy consumption (BP p.l.c. 2008), which makes it by far the biggest energy consumer in total as well as per capita. Table 5 a shows the energy system 2008, a simplified representation showing energy sources, main conversion technologies, and energy utilization. Conti et al. 2008; OPEC 2006; and Steiger 2004 provide more detailed information. Overall, 43% of primary energy consumption is converted into heat for industrial or residential purposes, 28% is used to generate kinetic energy for transportation, and 29% is used in electricity production. 90% of the conversion processes are based on combustion and in case of further conversion steps in thermal engines, they are limited to Carnot's laws. It should be noted that 94% of primary energy is derived from fossil and nuclear fuels, and the overall conversion efficiency rate is around 61%.

The abstraction process discussed in section 3 revealed six key features that future energy systems should possess. Using these features, Table 4 b displays a quantitative, normative energy scenario for 2060. The total amount of energy utilized is the same as in 2008, but conversion technologies were assumed to be more efficient. Nevertheless, the total primary energy needed is slightly higher than in 2008 due to a higher percentage of renewable energy sources that typically have lower efficiency rates in their conversion processes. Since renewable energies are sustainable and free of charge, primary energy consumption is of less significance in a system that is 42% nonfuel based.

[3] Fuel cells work at efficiencies of 50% – 60% (Spliehoff 2006), multiplied by typical efficiencies for electric motors of 90%.

Table 5 Simplified U.S. energy system 2008 and a future energy scenario for 2060 in the United States.

a) Simplified energy situation in the United States (2008)

	Energy source	Share [1]	Total	Share (fossil fuel)	Conversion Technology	Average efficiency [2]	Energy utilization	Share	Total
	Petroleum	25%	28%	25%	Combustion engine	22%	**kinetic energy**	5.5%	6%
	Biofuels	3%			Combustion engine	22%	(for transportation)	0.7%	
	Petroleum	14%	43%	43%	Combustion	90%	**Heat**	12.6%	39%
	Natural gas	18%			Combustion	93%		16.7%	
	Coal	11%			Combustion	87%		9.6%	
	Coal	14%	29%	26%	Clausius Rankine cycle	45%	**Electricity**	6.3%	14%
	Natural gas	6%			Combined cycle	58%		3.5%	
	Nuclear	6%			Clausius Rankine cycle	37%		2.2%	
	Renewables [3]	3%			80% hydro	70%		2.1%	
Sum		**100%**	**100%**						**59%**
Fossil fuel / Renewable Sources				**94% / 6%**					
Fuel based				**97%**					
Average fuel efficiency [3]						**61%**			

The total energy utilization is defined as constant for this scenario. ⇕

b) Energy scenario for the United States (2060)

	Energy source	Share [4]	Total [5]	Share (fossil fuel)	Conversion Technology	Average efficiency [2]	Energy utilization	Share	Total
	Petroleum	8%	13% (20%)	8%	Combustion engine	26%	**Kinetic energy** (for Transportation)	2.2%	6%
8	Bio fuels	4%			Combustion engine	26%		1.1%	
→	Electricity	0% (3%)			Battery, electric motor	85%		2.9%	
7 →	Geothermal, Solarthermal, Heat pump	19% (24%)	45% (53%)	17%	Heat tranfer	60%	**Heat**	13.0%	39%
	Biomass	9%			Combustion	85%		7.2%	
	Gas	12%			Combustion	93%		11.2%	
6	Coal	5%			Combustion	87%		4.4%	
→	Exhaust heat	0% (3%)			Heat transfer	100%		3.2%	
	Coal	10%	43% (30%)	21%	Clausis Rankine cycle	47%	**Electricity**	4.5%	14% (24%)
	Gas	4%			Combined cycle	60%		2.3%	
	Nuclear	7%			Clausius Rankine cycle	40%		3.0%	
	Renewables[3]	23% (10%)			Energy mix [10]	45%		4.3%	
Sum		101% (104%) [9]	101% (104%) [9]						**59%**
Fossil fuel / Renewable sources				**46% / 54%**					
Fuel based				**58%**					
Average fuel efficiency [3]						**66%**			

1: Market data (BP p.l.c. 2008; Conti et al. 2008; OPEC 2008; U.S. Dept. of Energy 2007).

2: Technological data (B.D.A. GmbH 2008; Neij 2008; Schindler and Zittel 2007; Tesla Motors Inc. 2008; U.S. Dept. of Energy 2008).

3: Values in brackets are the actual values without considering energy flows.

4: Values in brackets are the actual values considering primary energy sources.

5: Combined heat and power. Fifty percent of all power plants will reuse their waste heat. Thirty percent of the energy can be used (21% * 0.5 * 0.3 = 3%).

6: Renewable heating technologies, especially heat pumps, need electricity to operate. On average the electricity amount is about 10% (21% * 0.1 = 2%; 2% / 0.45 = 5%; 19% + 5% = 24%).

7: Electricity for transportation is stored in batteries and finally used in electric motors (7% * 0.45 = 3%).

8: The value in 2060 is higher than 100% in 2008 because renewable energies cannot be converted as efficiently as fossil fuels. In a highly nonfuel based scenario this value is not relevant. The actual value in brackets is by 3% higher because of reuse of waste heat.

9: The renewable energy mix's average efficiency is 45% using the assumed data (share / efficiency): Solar PV (25% / 45%), Solar Th (15% / 20%), Wind (25% / 51%), Geothermal (15% / 20%), Hydro (15% / 88%), Waves&Tidal (5% / 40%).

A variety of measures contribute to the improvement of the energy system. The share of renewable energy sources increased from 6% in 2008 to 54% in the given period. In 2060, 50% of all fuel based power generation facilities will co-generate heat and power, which translates to a 3% overall saving on required primary energy sources. A share of 30% of total heat utilization will be provided by renewable and direct heat sources such as geothermal, solar thermal, and heat pumps. In the transportation sector almost half of the kinetic energy will be provided by electric drive trains. The well-to-wheel efficiency of a 100% sustainable battery-based drive train system, using the renewable energy mix (Table 5b) will be around 38% compared to 26% of combustion engines by that time.

The example shows how an energy system can be improved significantly by incorporating key features that satisfy scientific principles and laws of sustainability. The designed scenario is a normative solution based on such key features. However, it is not the only solution. Slightly different proposals can be achieved as well using the same key features. In general, technological improvement, discovery of better ways to harness renewable energies, and supporting legislation will be crucial for the implementation of new optimized energy systems.

BOTTOM-UP PROGNOSIS ON POWER GENERATION TECHNOLOGIES

In the energy scenario for the United States in 2060, electricity will play a large role not only for end-use applications but also as an intermediate energy type. In the U.S. energy scenario (Table 5), the required electricity increases by 171% in the time period from 2008 to 2060, assuming constant total energy use. The reason is that 50% of the transportation in 2060 will be powered by electricity and renewable heating applications will need additional electricity as well. In the developed scenario, electricity from renewable energies was set at a high share in order to achieve the defined key features for the scenario.

In fact, it is hard to predict which technologies eventually will provide the needed electricity. Since electricity is a commodity consumer product, the production price is the crucial factor for the market success of specific conversion technologies. Political restrictions or support, subsidies, costs associated with greenhouse gas emissions, fuel accessibility, and public acceptance can distort the free market decisions. In the following sections, a bottom-up analysis is given to show the potential of different electricity generation technologies according to production prices, including costs on greenhouse gas emissions and electricity storage for intermittent power sources. State-of-the-art electricity production prices using different technologies were analyzed in several studies (Capital E 2004; Deutch and Moniz 2003; Langcake 2003; Weindorf 2003). Figure A.1 shows an overview of publication results and the calculated average production prices. Its segmentation into partial costs was subject of a previous study (Spliethoff 2006) and is applied to average production prices in Figure 6.

5.1. Driving Parameters for Electricity Production Costs

To enable a bottom-up analysis, the main parameters that affect electricity production costs in power plants are identified. They are categorized into initially fixed- and variable-cost drivers. In this analysis, costs are defined as price per unit, multiplied by unit demand. Variable cost drivers comprise fuel prices per unit, specific maintenance prices, and specific prices associated with emissions. The fixed cost drivers are initially set when the plant is built. They comprise total installation costs based on labor and engineering, material prices per unit, material demand, fuel demand, maintenance demand, CO_2 emission quantity, electricity storage demand, electricity storage price per unit, power plant efficiency, and power plant lifetime. The total cost prognosis is based on the development of the mentioned driving parameters. Due to missing data, the change in maintenance costs and the change in power plant lifetime are assumed constant in this analysis. All other cost drivers are outlined in detail in the appendix and will be discussed briefly here.

Fuel prices per unit. Table B.1 shows the significant fuel price increases between 2003 and 2008. Depending on the fuel, the average compounded annual growth rate (CAGR) during that time period ranged between 12% and 32%. The fuel prices in the model are projected to continue growing at 3% to 4% CAGR until 2025 (Bloomberg 2008; BP p.l.c. 2008; Conti et al. 2008; Schindler and Zittel 2007).

CO_2 emission price per unit. To keep the ecosystem in equilibrium, greenhouse gas emissions have to be limited. The cap and trade system in Europe is a promising approach and has the potential to be used worldwide. An analysis by Deutsche Bank implies a 2008 EU emission allowance (EUA) price of €40/t, which will reach €67/t in 2020 (Deutsche Bank 2008). Table B.2 shows an estimated average emission allowance price for developed countries until 2025, based on the Deutsche Bank study for Europe.

Production, installation, and engineering (PIE) costs. These costs are projected to improve at an average rate of around 0.2% CAGR for mature fossil fuel power plant technologies. Renewable energy plants have higher improvement potentials. For example, photovoltaic reaches maximum improvement rates of 6.1% CAGR between 2015 and 2020, followed by wind technology with an improvement rate of 2.6% p.a. between 2008 and 2015. Table A.1 shows an overview of enhancement potentials for all considered technologies. Projections are performed based on results of the experience curve approach for different power generation technologies (Neij 2008).

Material prices per unit. These have grown since 2003 at approximately 2% to 10% CAGR and will continue to rise but not at the pace of fuel prices. Table B.3 shows material price developments (Baukosteninformationszentrum Deutscher ArchitektenKammern GmbH 2008; Bund der Energicverbraucher 2008).

Material demand. The enhancement potential of material demand behaves similarly to the development of PIE costs. Table A.2 shows details.

CO_2 emission amount. In Table A.3, the emissions (CO_2 equivalent) throughout a plant's life cycle are listed for different power plant types. The analysis was performed by the Paul Scherer Institute and has been subsequently summarized (Deutsche Bank Research 2008).

Electricity storage demand. Within the considered power sources, solar- and wind-based technologies are considered as intermittent sources. Wind energy is considered as 50% less reliable than solar energy. Statistical data show that the sun's energy availability better suits to typical electricity consumption patterns. Due to low grid penetration of intermittent power sources in 2008, the share of necessary storage of intermittent electricity is as low as 5% to 7.5% of the produced electricity. In 2025, the share is projected to be 35% for solar energy sources and 53% for wind power (Table A.4).

Electricity storage prices. Electricity storage costs around 0.04$/KWh in 2007 (Zweibel et al. 2007) and is expected to decrease to 0.03$/KWh in 2025. Table B.4 shows the total electricity storage cost development per electricity production unit for solar- and wind-based energy sources.

Power plant efficiency. Currently dominating, fossil and nuclear fuel power plants are all restricted to Carnot's laws. Efficiencies range from 37% (nuclear) to 58% (gas-combined cycle) in 2008, but will only increase by a couple percentage points until 2025. Conversion systems for renewable energy sources vary between 15% (photovoltaic) and 87% (hydro). New, not mature technologies have higher potential to increase their efficiencies in the coming decades. Table A.5 shows details used in the model (Danish Wind Industry Association 2008; Gerl 2007; Karl 2006; Lawrence Berkeley National Laboratory 2002; Müller 2007; Swissnuclear 2008).

5.2. Interdependencies of Driving Parameters

The identified cost-drivers affect total electricity production costs. The interdependencies of the partial elements for a production cost prognosis are determined in Eq. 1.2. As stated before, costs are defined as price per unit multiplied by unit demand at the efficiency of the reference plant (t = 2003). Efficiency and lifetime variation have no impact on costs for storage or emissions. The developed formula calculates electricity production prices, reflecting the prices immediately after plant's construction. Hence the results will illustrate snapshots of all technologies and their development over time.

$$P(t) = [Fc(t) + Matc(t) + PIEc(t) + Mc(t)] * \frac{\eta(t-1)}{\eta(t)} * \frac{LT(t-1)}{LT(t)} + Sc(t) + CO_2c(t) \qquad (1.2)$$

P:	Total electricity production price	η:	Efficiency
Fc:	Fuel costs	LT:	Life time
Matc:	Material costs	Sc:	Storage costs
PIEC:	Production, installation & engineering costs	CO_2c:	Costs due to sanctions on emissions
Mc:	Maintenance costs	t:	time

If the intention were to calculate today's or future electricity generation prices of power plants that were built in the past, the fixed cost drivers of the construction date, but the variable cost drivers of the observation time have to be used in Eq. 1.2. The Eq. 1.2 can further be optimized by including time value of money calculations and also by including capital costs of debt financing.

5.3. Prognosis Results on Power Generation Technologies

The prognoses on electricity production costs, shown in Figures 5 and 6, are the modeling results of parameter prognoses in combination with the developed formula (Eq. 1.2). The result is not an accurate forecast on electricity production costs, but rather it shows the main portion of costs and probable future trends. The cost segmentation, shown in Figure 6, clearly depicts the impact of different cost drivers for different technologies

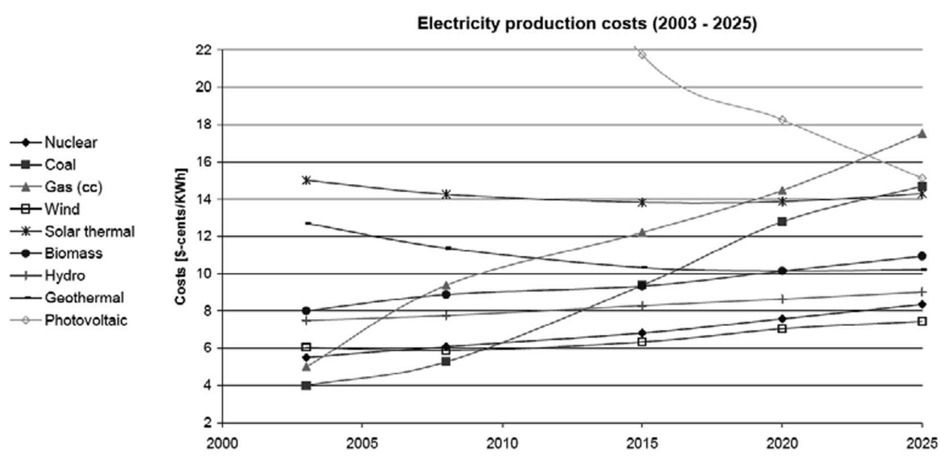


Figure 5 Electricity production costs development (2003–2025).

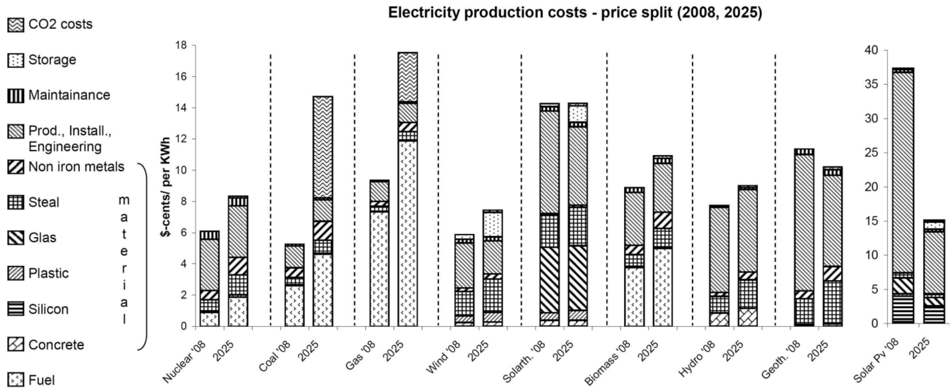


Figure 6 Electricity production costs—price split (2008, 2025).

and shows improvement potentials. Tables A.1, A.2, and A.5 set the benchmarks for research and development of new technologies in order to achieve the values of Figures 5 and 6.

Fossil fuel based power generation technologies are predicted to show rising electricity production costs. Increasing fuel prices and also costs for CO^2 emissions penalize those technologies and due to technological maturity, the possibility for improvement is limited.

On the other hand, technologies to convert renewable energy sources have higher improvement potential, are independent from fuels, and emit minimal amounts of greenhouse gases. These technologies are slightly more sensitive to rising material prices due to higher material demand. A variety of renewable energy technologies might have the ability to reach cost competitiveness, but major research tasks remain. Photovoltaic cells are favored by scientific principles but will not reach cost parity with other sources in the next twenty years, even though the underlying benchmarks (Tables A.1, A.2, A.5) are set to high improvement rates. These rates force the efficiency of photovoltaic cells to improve by 7% p.a. and purport a reduction of required material and production process costs of 5% p.a. Wind energy is already close to cost parity with currently established technologies. It has the best chance to scale renewable energy sources to some extent in the mid-term perspective.

The cost projections depend on analyses of initial production costs (Capital E 2004; Deutch and Moniz 2003; Langcake 2003; Weindorf 2003) and associated cost driver forecasts. In general, the costs are averages and might vary individually. Regarding renewable energy power plants the site's energy source accessibility has a significant impact on total cost variations. Overall, Figure 5 shows the result for the most probable development according to the proposed model. As expected, significant research in renewable energy technologies is needed for these to become economically competitive (Tables A.1, A.2, A.5), but political pressure against environmental pollution and rising fuel prices will support a focus on sustainable technologies.

CONCLUSIONS

The holistic method to seek an optimized energy concept for the future consists of a system analysis of the use of energy, a normative scenario, and a bottom-up analysis on possible implementation technologies.

Most forecast and scenario analyses on the future of energy use extrapolatory or exploratory approaches based on the past and present experience of the world and provide information on what might happen. Such well known publications (e.g. the Annual Energy Outlook, the IEA Energy scenarios, or the Shell energy scenarios) provide implications for strategic decision-making. Planners in research, industry, finance, and politics use those publications as guidelines to plan response strategies and by doing so, the prognosis becomes more probable.

Our opinion is that normative scenarios, which follow the principles of scientific optimization and sustainability, deserve more attention and should be developed and consulted to provide guidelines in the active shaping of future energy systems. The holistic method presented in this article can be used in designing such desirable system scenarios. The method has been applied to a globally applicable system analysis on energy, a design of an energy scenario for the United States in 2060, and a bottom-up analysis to evaluate the potentials of crucial power generation technologies.

The resulting energy scenario for 2060 consists of carefully matched, integral elements, but it only represents an exemplary framework. More detailed scenario designs should be created, considering more parameters. In particular, the integration of extensive climate models (e.g. Sokolov et al. 2004) setting quantitative environmental aims could upgrade the proposed qualitative key feature ‘‘consideration of environmental impact’’.

The upcoming extensive investment decisions especially on power plant technologies are long-ranging and will have a large impact on the design of the worldwide future energy system. Possible research endeavors and wise policies have the power to affect the free market decisions within the worldwide energy system. The proposed method is intended to guide decision-makers in research, industry, finance, and politics to focus on scientifically optimized, sustainable and, certainly at some point in the future, most profitable energy systems.

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APPENDIX A. POWER PLANT SPECIFIC DATA

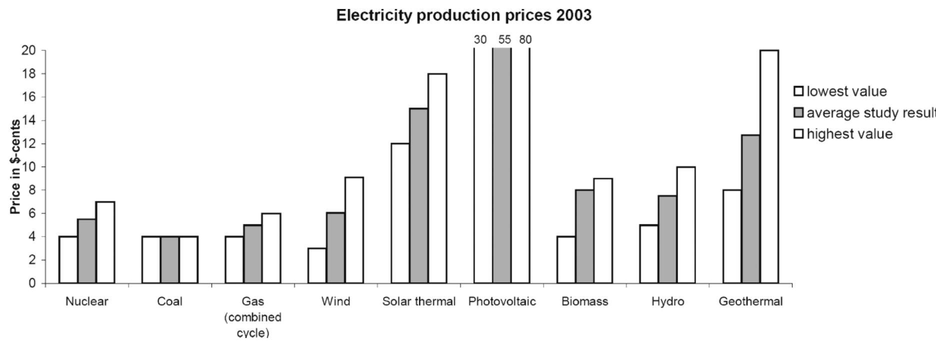

Fig. A.1 Electricity production prices.

Table A.1 Production, Installation & Engineering costs.

	Costs [$/KW/h]	CAGR			
	2003	2003–2008	2008–2015	2015–2020	2020–2025
Nuclear	0.035	–0.002	–0.001	–0.002	–0.002
Coal	0.014	–0.002	–0.001	–0.002	–0.002
Gas (combined cycle)	0.013	–0.002	–0.001	–0.002	–0.002
Wind	0.034	–0.021	–0.031	–0.021	–0.006
Solar thermal	0.078	–0.021	–0.023	–0.017	–0.006
Photovoltaic	0.458	–0.044	–0.050	–0.083	–0.069
Biomass	0.036	–0.010	–0.006	–0.006	–0.002
Hydro	0.055	–0.002	–0.001	–0.002	–0.002
Geothermal	0.103	–0.021	–0.031	–0.021	–0.017

Table A.2 Material demand.

	Demand [Kg/KWh]	CAGR			
	2003	2003–2008	2008–2015	2015–2020	2020–2025
Nuclear	individually	–0.002	–0.001	–0.002	–0.002
Coal	individually	–0.002	–0.001	–0.002	–0.002
Gas (combined cycle)	individually	–0.002	–0.001	–0.002	–0.002
Wind	individually	–0.019	–0.020	–0.019	–0.010
Solar thermal	individually	–0.019	–0.020	–0.019	–0.010
Photovoltaic	individually	–0.037	–0.038	–0.054	–0.037
Biomass	individually	–0.002	–0.001	–0.002	–0.002
Hydro	individually	–0.002	–0.001	–0.002	–0.002
Geothermal	individually	–0.010	–0.006	–0.004	–0.002

Assumption: all materials develop the same for each technology

Table A.3 CO_2 emission amount.

	CO_2 equivalent [g/KWh]	CAGR			
	2003	2003–2008	2008–2015	2015–2020	2020–2025
Nuclear	19	const.	const.	const.	const.
Coal	1080	const.	const.	const.	const.
Gas (combined cycle)	522	const.	const.	const.	const.
Wind	24	const.	const.	const.	const.
Solar thermal	30	const.	const.	const.	const.
Photovoltaic	217	const.	–0.091	–0.091	–0.091
Biomass	30	const.	const.	const.	const.
Hydro	20	const.	const.	const.	const.
Geothermal	30	const.	const.	const.	const.

Table A.4 Electricity storage demand.

	Storage fraction				
	2003	2008	2015	2020	2025
Wind	0.000	0.075	0.300	0.450	0.525
Solarthermal	0.000	0.050	0.200	0.300	0.350
Photovoltaic	0.000	0.050	0.200	0.300	0.350

Table A.5 Power plant efficiency.

	Efficiency	CAGR			
	2003	2003–2008	2008–2015	2015–2020	2020–2025
Nuclear	35	0.011	0.008	0.005	0.005
Coal	45.5	0.004	0.005	0.004	0.000
Gas (combined cycle)	58	0.002	0.001	0.002	0.002
Wind	40	0.015	0.016	0.008	0.004
Solar thermal	16	0.012	0.008	0.011	0.010
Photovoltaic	12	0.046	0.076	0.070	0.052
Biomass	43	0.005	0.006	0.004	0.004
Hydro	86	0.001	0.001	0.001	0.001
Geothermal	16	0.012	0.008	0.011	0.010

APPENDIX B. MARKET DATA

Table B.1 Fuel prices.

	Price per unit	CAGR			
	2003	2003–2008	2008–2015	2015–2020	2020–2025
Oil	30 [$/bbl]	0.32	0.02	0.02	0.05
Coal	32.95 [$/short ton]	0.12	0.03	003	0.04
Gas	4.5 [$/mmbtu]	0.19	0.02	0.02	0.05
Uranium (U308)	30 [$/lb]	0.28	0.04	0.04	0.05

Table B.2 CO_2 emission prices.

	Price				
	2003	2008	2015	2020	2025
Europe:	0 [€/t] 0	40 [€/t]		67 [€/t]	
OECD average:	[$/t]	0 [$/t]	30 [$/t]	54 [$/t]	60

Table B.3 Material prices.

	Price [$/Kg]	CAGR			
	2003	2003–2008	2008–2015	2015–2020	2020–2025
Concrete	0.075	0.02	0.02	0.02	0.02
Silicon	25	0.1	0.04	0.02	0.01
Plastic	2	0.04	0.04	0.04	0.04
Glas	4	0.02	0.02	0.02	0.02
Steal	1	0.05	0.04	0.03	0.03
Non iron metals	2	0.05	0.04	0.04	0.04

Table B.4 Electricity storage prices.

	Price [$/KWh]				
	2003	2008	2015	2020	2025
Storage	–	0.04	0.036	0.033	0.03