PAUL SCHERRER INSTITUT

Methane from Wood

Assessment of Wood-Based Synthetic Natural Gas Technologies with the Swiss MARKAL Model

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Table of Contents

1. Introduction

Biomass-based energy carriers could play an important role in the energy system. Conversion of biomass into high quality, flexible final-energy carriers constitutes a convenient vehicle to "add value" to biomass as an energy resource. Being clean and low-carbon-intensive, biomass-based energy carriers could contribute to displace carbon-intensive fossil fuels from the energy markets, reducing greenhouse gas emissions and bringing benefits in terms of security of energy supply, among others.

Today, the contribution of biomass to the energy supply of Switzerland is still very small and mainly concentrated in the electricity generation and residential heating sectors. However, there appears to be a sizeable potential for the future expansion of bio-energy (BfE, 2004). In addition, the Swiss government is supporting an increase of the share of renewable energy sources within the energy mix of the country (IEA, 2004). Currently, it is being discussed which the most convenient pathways for energy uses of biomass in the long term could be.

The ECOGAS project, sponsored by the novatlantis initiative of the ETH domain as well as commercial partners, pursues research, development, demonstration and deployment[1] of technologies that allow the conversion of wood via gasification to synthetic natural gas (bio-SNG) and/or electric power. Within the ECOGAS project, the Paul Scherrer Institute (PSI) is responsible for management and development of individual processes, specifically a wood gasification process representing a promising option for an efficient conversion of solid wood into bio-SNG (novatlantis, 2003; Stucki, 2003). Complementary initiatives are taking place at the EU level.

Bio-SNG can be produced from many types of wood feedstocks with a high efficiency and can be used in a clean and efficient manner. Moreover, converting wood into bio-SNG allows benefiting from the existing natural gas transmission and distribution insfrastructure. Bio-SNG could be injected into the natural gas grid and used to fuel natural gas-based vehicles, decentralized combined heat and power (CHP) facilities or directly in gas heating devices in the residential sector. Being CO_2 neutral, the use of bio-SNG would contribute to strengthen the decarbonization effects of natural gas, which is the less carbon-intensive fossil fuel. Also, if used to fuel natural gas-based vehicles, bio-SNG could contribute to reduce the significant dependence of the Swiss transportation sector on petroleum-based energy carriers.

In order to conduct a comprehensive assessment, it is necessary to evaluate the economic and ecological performance of wood-based energy technologies in the context of the Swiss energy system. Competing routes for the use of wood to satisfy energy needs have to be considered. Moreover, the competition between biomass-based energy technologies and other renewable and non-renewable-based energy technologies must be examined. This calls for the use of a methodological tool that allows a comprehensive representation of the existing and possible future energy resources, energy carriers and supply and end-use technologies in the Swiss energy system.

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[1] Research, development, demonstration and deployment activities can be summarized as RD3 (PCAST, 1999)

Herein, the role of wood-based energy technologies in the Swiss energy system in the long-term is examined using the energy-system Swiss MARKAL model. The Swiss MARKAL model is a "bottom-up" energy-systems optimization model that allows a detailed representation of energy technologies (Fishbone and Abilock, 1981, 1983; Loulou *et al.*, 2004). The model has been developed as a joint effort between the Energy Economics Group (EEG) at Paul Scherrer Institute (PSI) and the University of Geneva and is currently used at PSI-EEG.

Using the Swiss MARKAL model, this study examines the conditions under which wood-based energy technologies could play a role in the Swiss energy system, the most attractive pathways for their use and the policy measures that could support them. Given the involvement of PSI in the ECOGAS project as mentioned above, especial emphasis is put on the production of bio-SNG from wood via gasification and methanation of syngas and on hydrothermal gasification of woody biomass. Of specific interest as well is the fraction of fuel for passenger cars that could be produced by locally harvested wood.

The remainder of this report is organized as follows. Section 2 presents a brief description of the MARKAL model. Section 3 describes the results of the baseline scenario portrayed here, which represents a plausible, "middle-of-the-road" development of the Swiss energy system. Section 4 discusses results illustrating the conditions under which the wood-based methanation technology could become competitive in the Swiss energy market, the role of oil and gas prices, subsidies to methanation technologies and the introduction of a competing technology, namely the wood-based Fischer-Tropsch synthesis. Finally, section 5 outlines some conclusions from this analysis.

This report is one component of the assessment of SNG from wood and related wood-based energy technology pathways. Felder (2004) reports complementary analyses of the ecological impact of the use of methane from wood gasification using the Life Cycle Analysis (LCA) methodology.

2. The Swiss Energy-System MARKAL Model

The role of biomass-based energy technologies in the Swiss energy system is analyzed using the Swiss energy-system MARKAL model. The Swiss MARKAL model is a "bottom-up" energy-systems model that provides a relatively detailed representation of energy supply and end-use technologies. Here, the most relevant assumptions in the context of this analysis are described. A more detailed description of the Swiss MARKAL model can be found in Labriet (2003) and Schulz (2004).

The model has been developed as a joint effort between the Energy Economics Group (EEG) at Paul Scherrer Institute (PSI) and the University of Geneva and is currently used at PSI-EEG. The model is part of the MARKAL (MARket ALlocation) family of models (Fishbone *et al.*, 1983; Loulou *et al.*, 2004), a group of perfect-foresight[2], optimization energy-system models that represent current and potential future energy technologies. This kind of models is typically used to obtain the least-cost energy system configuration for a given time horizon under a set of assumptions about end-use demands, technologies and resource potentials.

The base year of the model has been calibrated to officially published Swiss energy statistics (BfE, 2001b) and to IEA statistics (IEA, 2002) of the year 2000, respectively, depending on the quality of the obtained data. Some relevant statistics as well as the model calibration for final-energy consumption of the year 2000 are presented in the Appendix 1.

The backbone of the MARKAL modeling approach is the so-called Reference Energy System (RES), i.e. a representation of currently available and possible future energy technologies and energy carriers from which the optimization model chooses the least-cost energy system and energy flows for a given time horizon and given end-use energy demands. Figure 1 presents a simplified version of the reference energy system (RES) used in the Swiss MARKAL model, which illustrates energy flows in Switzerland from production to the end-uses. Five main end-use sectors have been considered, namely agriculture, commercial, industrial, residential and transportation sectors with sub-categories representing specific uses such as heating, domestic appliances, etc and transportation modes. For the sake of simplicity, not all technologies and flows represented in the model are included in Figure 1.

In this analysis, a time horizon of 50 years, from 2000 until 2050, has been chosen and five-year time steps are used. The costs and potential of resources and costs, potential and technical characteristics of the technologies are time dependent. Unless reported otherwise, a discount rate of 5% is used in all calculations reported here. The currency units used in this report are US dollars of the year 2000 [US$]. For a better comparison of the report with Swiss statistics, important monetary values are also given in Swiss Franks [CHF] and Rappen [Rp].

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[2] Perfect foresight refers to the fact that the model operates under the assumption of a single, monolithic actor that is able to "foresee" the future and take optimal decisions in each time period that will lead to a least-cost energy system for the whole time horizon (Loulou *et al.*, 2004). Technically, an optimization is conducted simultaneously for all the time periods within the time horizon specified by the analyst.

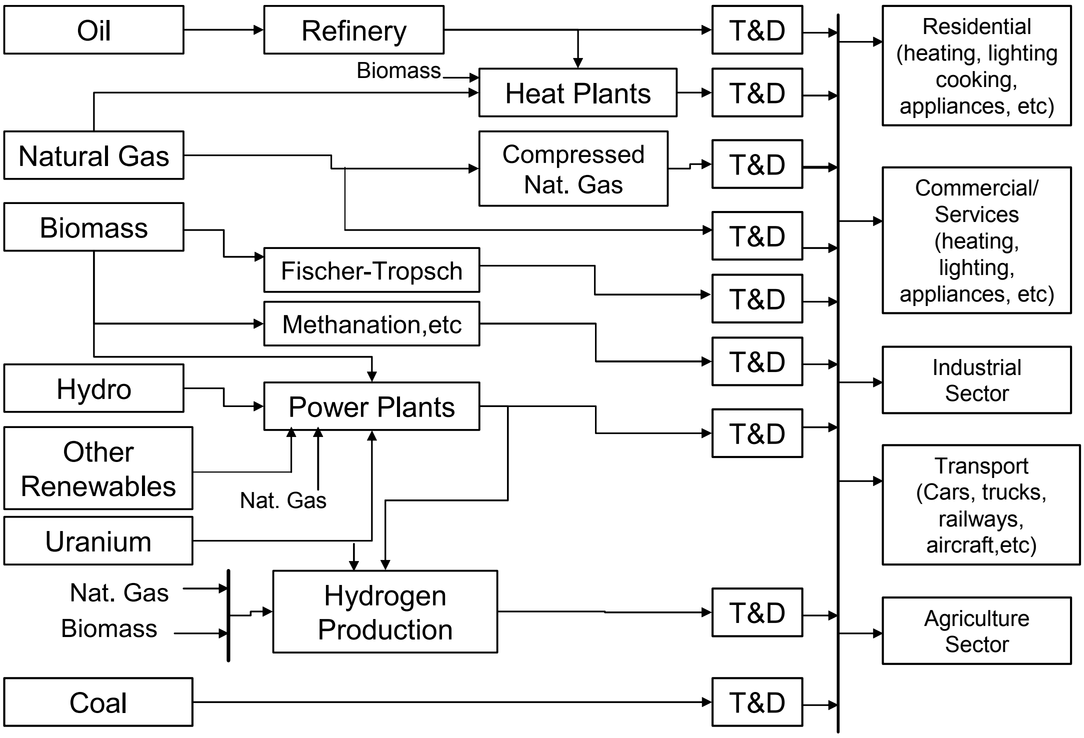

Figure 1: A simplified version of the Reference Energy System (RES) used in the energy-systems Swiss MARKAL model. T&D is an abbreviation for transmission and distribution.

For the evaluation conducted here, each wood-based energy process is embedded in a process chain that is linked to the energy production, transmission and distribution (T&D) system of Switzerland. Figure 2 to Figure 4 depict the process chains under examination in this study. In general, there are three types of process chains. The first type of chain includes processes that produce fuels for the transportation sector, namely bio-SNG and Fischer-Tropsch liquids (Figure 2). The second type of chain includes processes related to combined heat and power production from biomass (Figure 3). The third type of chain includes technologies for only heat production from biomass (Figure 4). In assessing the role of bio-SNG from wood, the very first chain is the most relevant. This chain represents the methanation plant, where methane is produced from wood gasification. The produced methane is injected into the Swiss gas grid and can be used in the transportation sector in compressed natural gas (CNG) passenger cars. We pay specific attention to its competitiveness in relation to alternative pathways in the Swiss energy system.

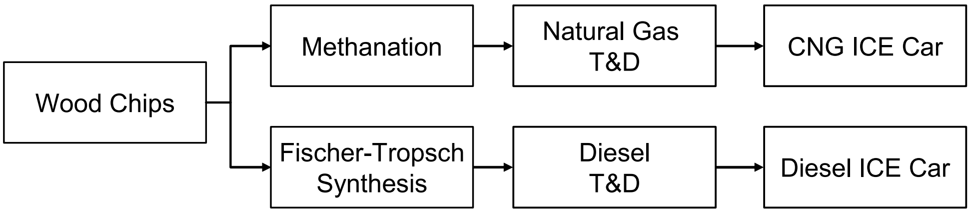

Figure 2: Wood-based process chains for bio-fuel production from wood considered in the Swiss MARKAL model.

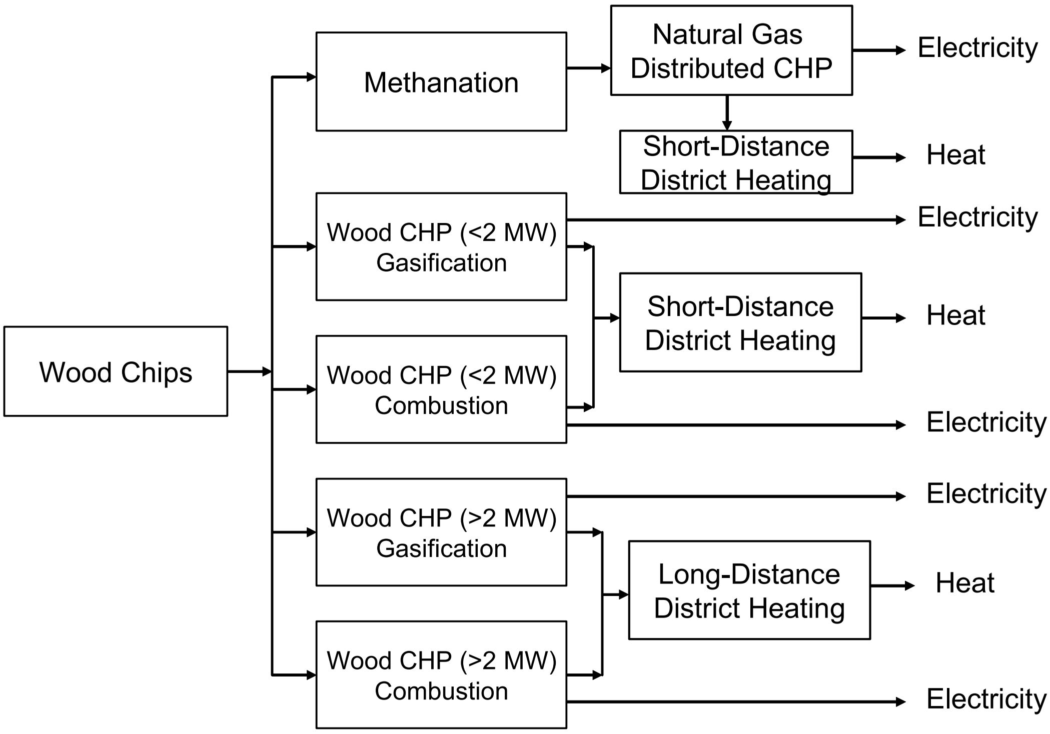

Figure 3: Wood-based process chains for combined heat and power (CHP) production considered in the Swiss MARKAL model. For simplicity, transmission and distribution processes are not shown in the diagram.

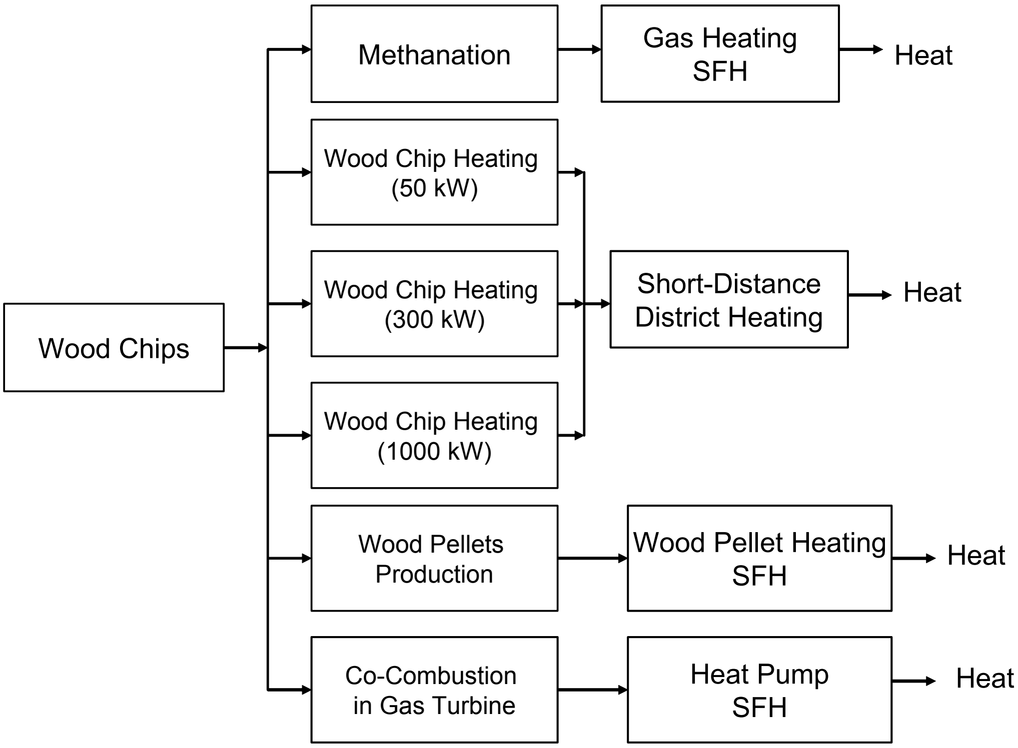

Figure 4: Wood-based process chains for heat production considered in the Swiss MARKAL model. The abbreviation SFH stands for Single Family Houses. For simplicity, transmission and distribution processes are not shown in the diagram.

Notice that the production of only electricity from wood has not been an object of investigation in this study as we have only considered combined heat and power

(CHP) facilities. This assumption reflects the status of the discussion about the role of biomass in Switzerland, where the actors involved tend to perceive that a facility producing only electricity would imply wasting the produced heat. However, the role of this option should be examined more carefully in future technology assessments.

3. The Baseline Scenario

In this section, we describe the main features of the baseline scenario that provides the context for our analysis of the role of wood-based energy technologies in Switzerland. In general, it can be said that "scenarios are alternative images of how the future might unfold and are an appropriate tool to analyze how driving forces may influence future outcomes and to assess the associated uncertainties" (SRES, 2000). The baseline scenario portrayed here depicts future trends in the energy system of Switzerland without any radical political, technical or social change. In this sense, it represents a plausible, "middle-of-the-road" development of the Swiss energy system.

It must be noticed that there can be many alternative development paths and huge uncertainties abound as to how the future energy system will unfold. Thus, although presenting alternative, highly contrasting scenarios is outside the scope of this study, on the basis of the baseline scenario we examine complementary scenarios in which we assign different values for key variables such as cost trends of key technologies, oil and gas prices and the introduction of subsidies, among others. These complementary scenarios, on the one hand, help examining the impact of uncertainties in baseline assumptions and, one the other hand, allow conducting "what if" analysis that could give assistance to the decision-making process.

3.1. Main Scenario Assumptions

In this section, the main assumption about population and Gross Domestic Product (GDP) growth, resource prices, wood potential and the transportation sector are described. A more detailed description can be found in Labriet (2003) and Schulz (2004).

Figure 5 illustrates the population and GDP growth in Switzerland in our scenario between the years 2000 and 2050. The population projection used in this scenario corresponds to the scenario "A-Trend" reported by BFS (2001), which is based in a continuation of recent historical trends and middle values for fertility rates, immigration flows and life expectancy. In this scenario, the population in Switzerland increases from about 7.2 million inhabitants in 2000 to about 7.4 million inhabitants around 2030. Afterwards, the population experiences a slight decline reaching about 7.1 million inhabitants in 2050. The GDP projection used here corresponds to the scenario reported by SECO (2004). GDP is assumed to increase by nearly 50 % from the year 2000 to the year 2050. In Figure 5, GDP is given in relative terms to the levels of the year 2000 (assumed as 100%).

Another important assumption concerns the prices of oil and natural gas resources for which moderate increments are assumed in the first half of the 21st century in this scenario (see Table 1). The crude oil price is assumed to constantly increase from 4.6 US$/GJ (equivalent to 29US$/bbl) in the year 2000 to 8 US$/GJ (equivalent to 50 US$/bbl) in the year 2050[3]. Natural gas, is assumed to be linked to the crude oil price.

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[3] In the model crude oil is refined among others to diesel, gasoline, kerosene, and heavy fuel oil. To calcualte the end user price for crude oil products additional variable cost for the operation of the

Hence the price increases from 3.3 US$/GJ in the year 2000 to 5.7 US$/GJ in the year 2050[4]. Given the large uncertainty that surrounds the development of the price of fossil energy resources, a sensitivity analysis is conducted in section 4.

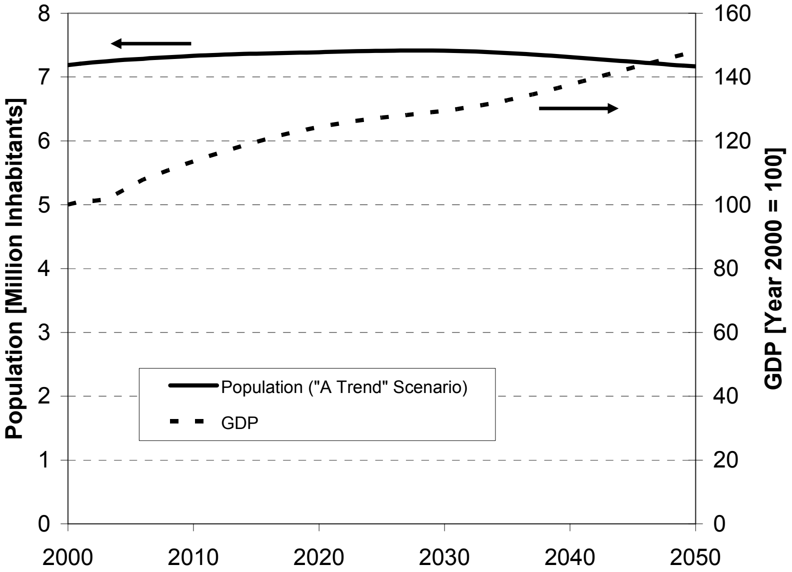

Figure 5: Population growth and GDP growth in Switzerland between 2000 and 2050 in the scenario portrayed in this study.

Table 1: Prices for fossil energy resources as assumed in this study. For a better understanding, the oil price is given both in US$/GJ and in US$/bbl.

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Natural Gas (US$/GJ)	3.3	3.6	3.8	4.0	4.3	4.5	4.8	5.0	5.2	5.5	5.7
Crude Oil (US$/GJ)	4.6	5.0	5.3	5.6	6.0	6.3	6.7	7.0	7.3	7.7	8.0
Crude Oil (US$/bbl)	29	31	33	35	37	39	41	43	45	47	50

Two important assumptions relate to the distribution costs and taxes. In general, the model includes distribution costs for all fossil recourses. However, the model does not contain taxes for any fuel use. Chapter 4 defines different levels of subsidies on methane. Since the model does not include taxes, the subsidies can be interpreted as a kind of tax exemption for methane to be used in the transportation and the other sectors. The subsidies levels introduced in the analyses remain well below the actual taxes level usually paid in the transportation sector.

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refinery of 2.3 US$/GJ and the distribution costs for diesel and gasoline have to be added. The distribution cost of diesel is assumed to be 0.88 US$/GJ and for gasoline 1.23 US$/GJ.

[4] The transmission cost of natural gas are assumed to be 1.00 US$/GJ.

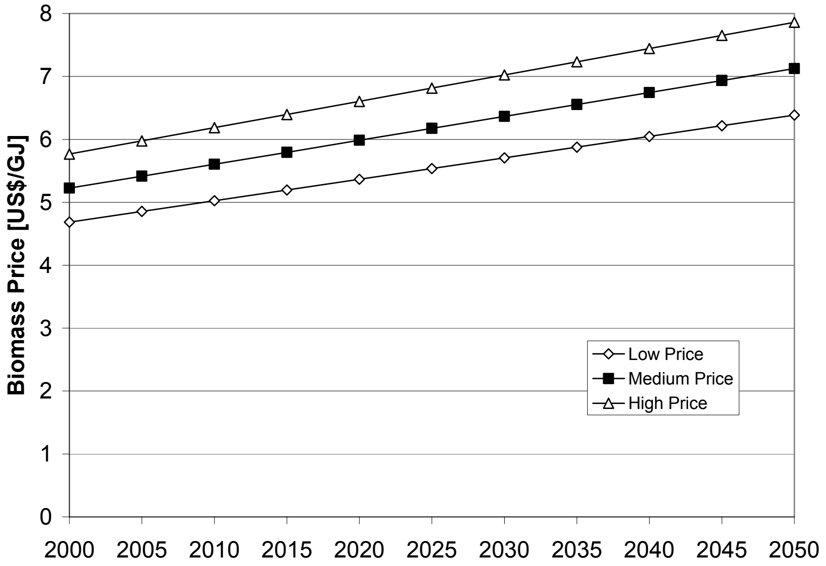

Figure 6: Development of the biomass price for the three categories considered in the scenario under examination here.

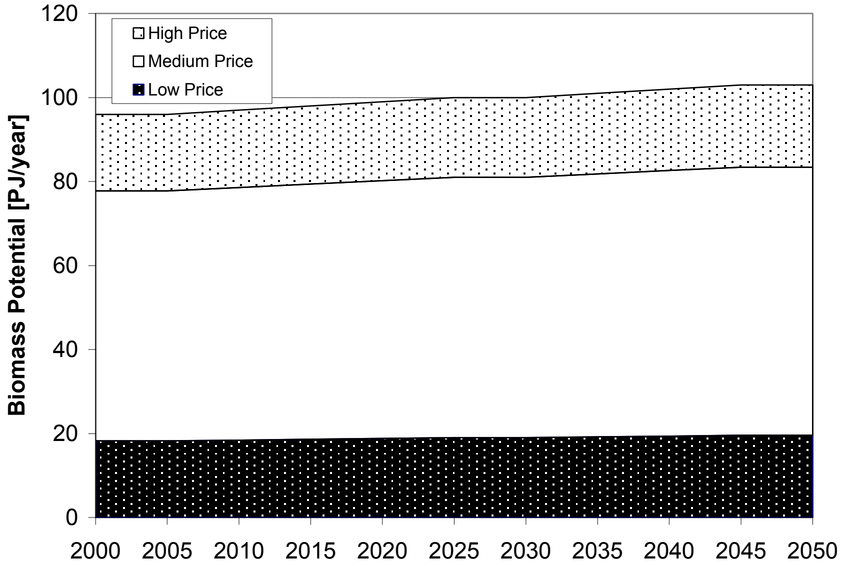

Figure 7: Biomass potential in Switzerland used in this scenario.

Figure 6 and Figure 7 illustrate the development of wood prices and potential in Switzerland assumed in this scenario between 2000 and 2050. The figures used here are based on BfE (2004), where theoretical potentials were estimated[5]. Additionally to the theoretical potential, BfE (2004) also defines an ecological potential, which amounts to about half the theoretical potential[6]. Despite the fact that some arguments favor to use the ecological potential as a basis for an analysis this report chooses the

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[5] The theoretical potential is defined in BfE (2004) as "based on the wood grown in productive land surfaces and the residues from secondary production and human consumption that be reutilized".

[6] The ecological potential is defined in BfE (2004) as "ecological net-production potential respectively the share of biomass that can be used for energetic treatment without material utilization".

theoretical simply because it reflects to total available biomass potentially harvested in Switzerland.

The theoretical biomass potentials considered in this analysis correspond only to the category "a" given in BfE (2004), which comprises "Waldholz, Feldgehölze, Obstbau"[7]. The total potential used here amounts to approximately 96 PJ/year in the year 2000 and increases only slightly to 103 PJ/year in the year 2050. This figure should be understood as an optimistic "ceiling" for the contribution of wood in Switzerland. Low-price, medium-price and high-price categories are distinguished. The low and high-price categories encompass 25 % of the total wood potential each and the medium price category comprises the remaining 50 % of the total wood potential (see Figure 7).

Pertaining to the wood technologies investigated within the scope of this analysis, two important assumptions are made in relation to the development of the costs over time. The investment costs of all new processes or processes that are still under development are reduced by 50 % from the starting year (2000) until the year 2020. Those technologies are the methanation process, the Fischer-Tropsch synthesis and the co-combustion of wood in a gas turbine with a subsequent heat pump. The investment costs of all wood technologies that are presently available on the market in Switzerland are reduced by 20 % over the next 30 years. Thereafter, we assume the costs to remain constant. Those technologies comprise all other wood technologies listed in Appendix 2 except for the ones mentioned above.

Moreover, each wood-based technology is implemented with the help of growth constraints. A growth constraint in the MARKAL model limits the maximal annual capacity increase for a given technology as expressed by equation (3.1). The formula states that the capacity of a technology *te* in the period *t* cannot be larger than the capacity in the previous period *t-1* multiplied by the growth rate. Additionally, a seed value must me added in order to initialize the constraint in the first period the technology is available for installation. The seed value is a very small value and usually equal to the "smallest" capacity of a technology. The growth rate for all wood technologies is set at 10 % per annum.

$$CAP_{t,te} \geq CAP_{t-1,te} \cdot (1 + growth\_rate_{te,t})^{\Delta t} + seed\_value_{te} \ , \qquad (3.1)$$

where:

$CAP_{t,te}$ is the capacity of a given technology te in period t
Δt is the period length
$growth\_rate_{t,te}$ is the annual growth rate of capacity for technology *te* in period *t*

Another important element of our scenarios is related to the future role of nuclear power plants within the Swiss energy system. In this scenario, we have assumed that the electricity generation from nuclear power plants remains constant at its year-2000 levels for the entire time horizon. This presupposes the replacement of nuclear plants scheduled to be decommissioned in the next decades but it does not assume the introduction of any new nuclear power plants. It must be recognized, however, that

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[7] "Waldholz, Feldgehölze, Hecken" include only natural wood assortments from forestry including hedges and biomass from fruit-growing. BfE (2004).

the future role of nuclear energy in Switzerland will depend, among other factors, on addressing the issues of higher nuclear safety, disposal of nuclear waste, proliferation resistance of fuel and public acceptance and the related political decisions on these topics.

As for the imports and exports of electricity, we have assumed that in the long-term exports will become equal to imports. Under this assumption, Switzerland remains independent from neighboring EU countries in terms of its electricity supply in the long-term.

3.2. Energy Consumption Trends and CO_2 Emissions

In order to give an adequate context to our analysis, in this section we describe the main characteristics of our baseline scenario, as quantified with the Swiss MARKAL modeling framework. Thus, we briefly present the trends in primary and final energy consumption and the CO_2 emissions in the baseline scenario.

Primary energy is defined as energy that is not subject to any additional conversion or transformation processes. Figure 8 illustrates the primary energy consumption of the baseline scenario in the period from the year 2000 to the year 2050. The total primary energy increases from about 1150 PJ in 2000 to about 1350 PJ in 2050. Oil remains the major fuel contributing to primary energy consumption with a share of about 43 % in the year 2050. Nuclear energy also remains an important primary energy resource but the share drops slightly form about 26 % in 2000 to about 21 % in 2050. The share of natural gas increases from about 9 % in 2000 to about 17 % in 2050 while wood resources are not used to a larger extent than they were in the year 2000. Due to an increasing use of heat pumps, latent heat[8] contributes about 43 PJ to the primary energy consumption balance in 2050.

In order to understand the details of Figure 8 the representation of hydro, nuclear and electricity has to be explained. Depending on the assumed efficiency of hydropower and nuclear power plants, the figures for primary energy consumptions have different values. In Figure 8 the efficiency of a hydro power plant is assumed to by 80 % and the efficiency of a nuclear power plant is assumed to be 33 %. These values correspond to those used in the Swiss Overall Energy Statistics from the Bundesamt für Energie (BfE, 2001b). Moreover, electricity is not a primary energy source. In Figure 8 electricity represents the net imports (imports – exports) of electricity.

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[8] In this context, latent heat represents ambient heat energy (Umweltwärme) used for heat pumps.

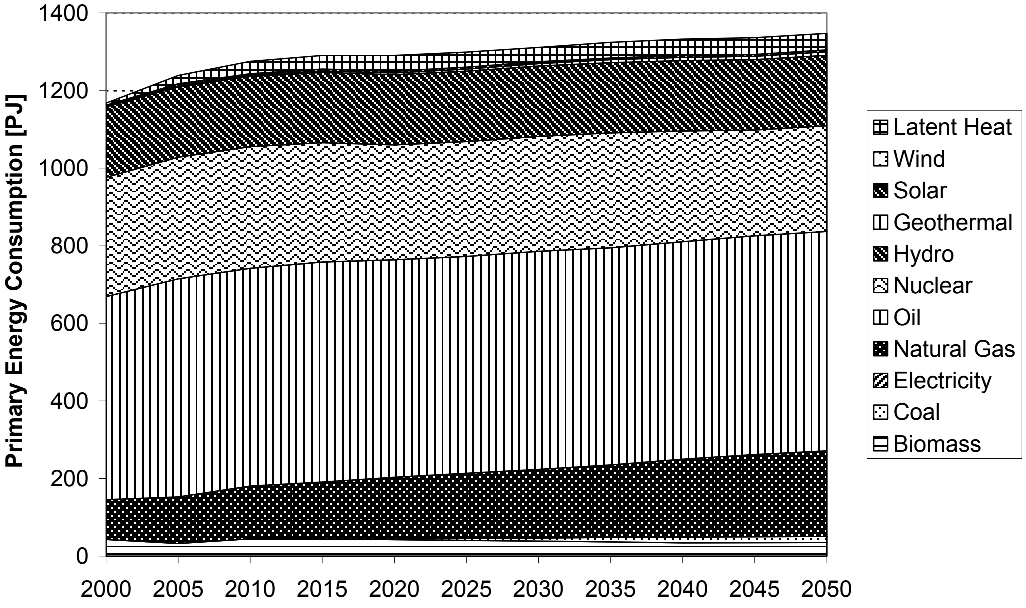

Figure 8: Primary energy consumption in the baseline scenario for the period 2000 to 2050.

Figure 9 and Figure 10 show the final energy consumption by sectors and by fuels for the baseline scenario. Final energy is defined as the energy that is available to the consumer. The total final energy consumption increases from about 885 PJ in 2000 to about 1022 PJ in 2050. The largest consumer of final energy is the transportation sector. The share of this sector increases from about 35 % in 2000 to about 43 % in 2050. The final energy consumption in all other sectors remains approximately constant with the exception of the residential sector whose share reduces from about 26 % in 2000 to about 21 % in 2050. The dominant fuels are oil products whereas the share of natural gas increases over the time horizon.

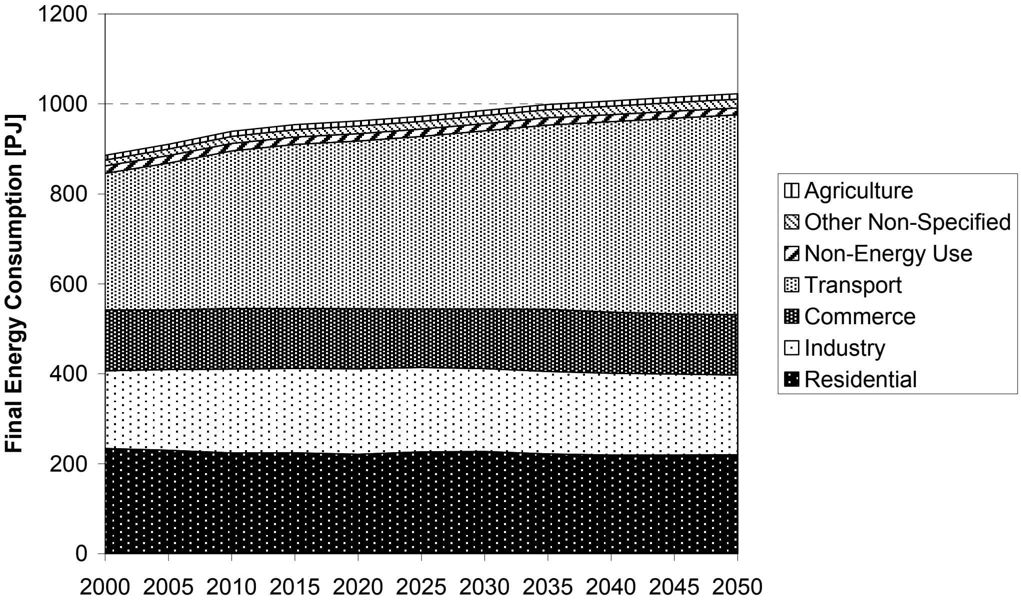

Figure 9: Final energy consumption by sectors in the baseline scenario for the period 2000 to 2050.

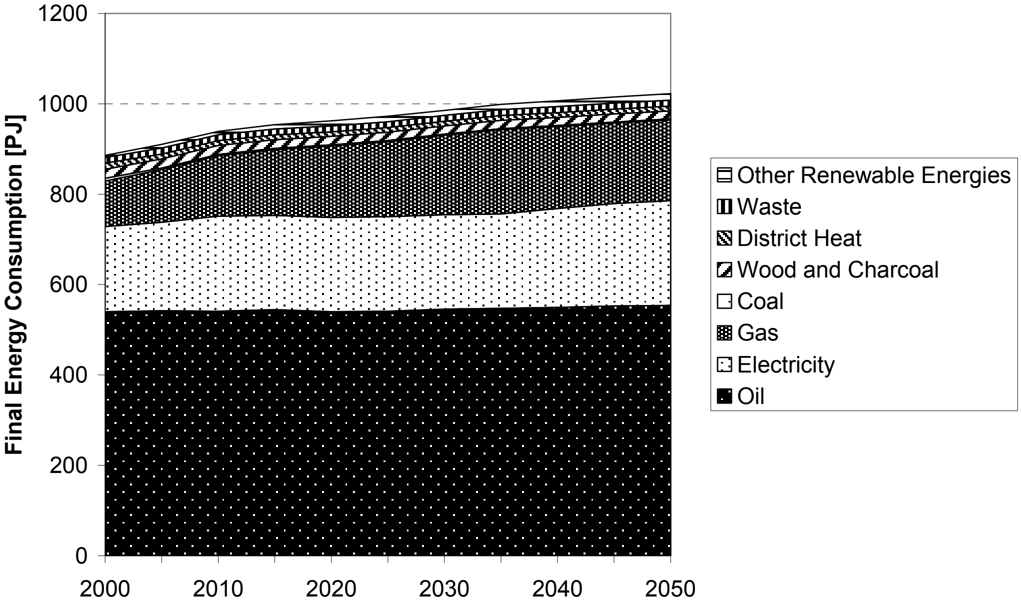

Figure 10: Final energy consumption by fuels in the baseline scenario for the period 2000 to 2050.

Figure 11 displays the CO_2 emissions for the baseline scenario. The emissions increase from about 45 million tons of CO_2 in the year 2000 to about 52 million tones (Mt) of CO_2 in 2050. This increase is mainly due to a significant growth of the energy consumption in the transportation sector, especially for passenger cars. Notice that the Swiss CO_2 law has not been considered in this baseline scenario.

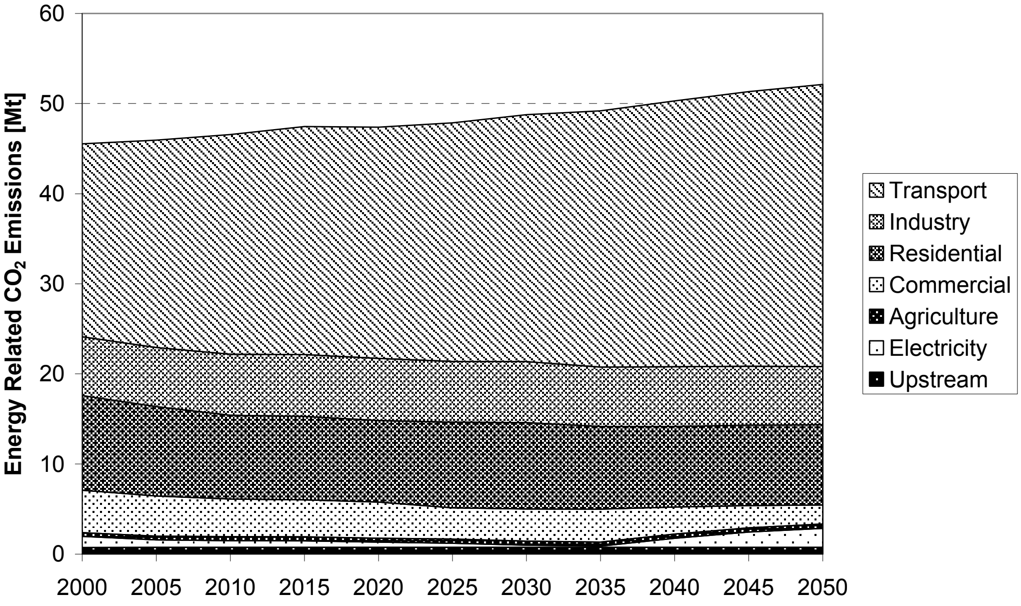

Figure 11: Energy-related CO_2 emissions per sector in Switzerland for the period 2000 to 2050 in the baseline scenario.

Figure 12 presents the final-energy consumption by fuel in the transportation sector under baseline conditions for the year 2050. As can be seen, oil products still dominate the transport sector in the long-term in this scenario. Notice that methanol from natural gas was considered as an option for meeting future demands in the transportation sector in our scenario. However, it should be noticed that a number of obstacles, not the least the need to deal with the toxicity of this fuel, surround the future perspectives of this technology.

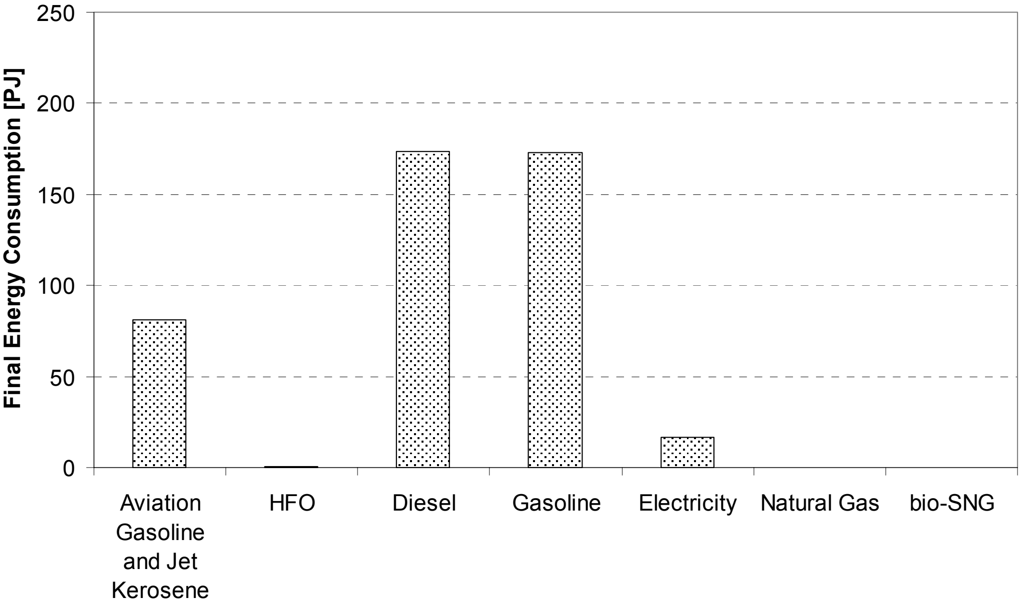

Figure 12: Final energy consumption by fuel in the transport sector in the year 2050 for the baseline scenario.

4. Assessment of Wood-Based Energy Technologies

This chapter describes the results obtained from the assessment of wood-based energy technologies using the Swiss MARKAL model as described above. The emphasis is thereby to find out under which conditions the wood technologies under examination, respectively the process chains depicted in Figure 2, Figure 3 and Figure 4 could gain importance in the Swiss context. Considering the importance of ECOGAS project, special attention is given to the wood methanation process to produce bio-SNG.

The methanation process converts wood to bio-SNG. There are three different options for the use of bio-SNG in the Swiss energy sector after it is fed into the national gas grid. On the one hand, bio-SNG can be used in the transportation sector to fuel passenger cars. On the other hand, it can be used in the residential sector. The residential sector opens the possibility to use bio-SNG in CHP plants (plant size: 0.5 MW) to generate electricity and heat, and to use it in gas-heating devices for producing heat in single-family houses.

The use of bio-SNG as fuel in the transport sector is in strong competition with a second wood-based technology, the Fischer-Tropsch synthesis. This process, based on biomass gasification, produces the so-called Fischer-Tropsch liquids, some of which can be used in the same way as conventional diesel (e.g. Tijmensen et al., 2002; Yamashita and Barreto, 2004).

The costs of the bio-SNG and Fischer-Tropsch synthesis technologies, especially the investment costs and the generation costs, are strongly dependent on the size of the plant. In this assessment, the costs of the methanation plant are based on a plant size of 100 MW whereas the costs of the Fischer-Tropsch synthesis are based on a plant size of 400 MW. Because of the difference in the economics of scale, the investment costs of the Fischer-Tropsch are slightly lower than those of the methanation plant (see Appendix 2).

Equation (4.1) shows how the generation costs of a given plant are calculated by the MARKAL model and illustrates how the investment costs directly influence the generation costs of an energy carrier.

$$GC = VAROM + \frac{FC}{EFF} + \frac{FIXOM}{AF} + \frac{INVCOST}{AF} \cdot CRF \tag{4.1}$$

$$CRF = \frac{(1+r)^t \cdot r}{(1+r)^t - 1} \tag{4.2}$$

GC:	Generation cost
VAROM:	Annual variable O&M costs
FIXOM:	Annual fixed O&M costs
FC:	Fuel costs
EFF:	Efficiency
AF:	Availability factor
INVCOST:	Investment cost
CRF:	Capital recovery factor

t: Lifetime
r: Discount rate

In this context, we should point out one important element before addressing the results in detail. Often only generation costs are used when comparing the competitiveness of different plants. This is an important indicator for a first evaluation step but it represents a static comparison. Moreover, using the generation cost as an indicator is difficult if co-generation plants are the objective of the comparison because of the issue of cost allocation between different output energy carriers. For this reason, a more comprehensive and dynamic comparison can be obtained by embedding the technologies of interest in an energy-system model, in our case Swiss MARKAL. In this way not only the generation costs of each technology are considered in the calculations but also the competitiveness of technologies in the different sectors, the competitiveness of technologies in relation to the demand of energy and the competitiveness of energy generation technologies compared to energy saving options e.g. an improved housing insulation.

Within the scope of this report, we analyze three different scenario sets. The first set of scenarios investigates the effect of increasing gas and oil prices on the introduction of wood-based energy technologies into the marketplace. We assume the oil price to be the driving force behind fossil resource prices. Thus, if for instance the oil price increases by 100 %, we assume that all other fossil resource prices increase by 100 % as well. Moreover, the increase of all fossil resource prices follows a linear gradient. In total, four scenarios are examined in this first set of scenarios, comprising oil price increases from 28 US$/bbl in 2000 to 100 US$/bbl, 110 US$/bbl, 120 US$/bbl and 130 US$/bbl in 2050, respectively.

The second scenario set places subsidies on synthetic natural gas. The oil price grows to a maximum of 50 US$ in 2050 just as in the baseline scenario. This set of scenarios consists of five scenarios with different subsidy levels. The subsidies of the scenarios are as high as 6 US$/GJ (3.24 Rp/kWh), 7 US$/GJ (3.78 Rp/kWh), 8 US$/GJ (4.32 Rp/kWh), 9 US$/GJ (4.86 Rp/kWh) and 10 US$/GJ (5.40 Rp/kWh), respectively.

The third scenario set analyses the effect of an oil price increase to a more likely level of 70 to 80 US$/bbl in 2050 compared to 100 US$/bbl or more. Additionally to the oil price increase, a lower subsidy of only 4 US$/GJ (2.16 Rp/kWh) to 5 US$/GJ (2.7 Rp/kWh) is introduced. Hence, the last scenario set is a combination of the previous scenarios where less drastic increases in the fossil resource prices and lower subsidies for synthetic natural gas are assumed.

Table 2 summarizes the scenario sets analyzed within the scope of this study.

As mentioned above, if a Fischer-Tropsch (FT) plant were built in Switzerland the scale of choice would be at least 400 MW, in order to be able to exploit the associated economies of scale. However, it is very unlikely that a FT plant of this scale could be built in Switzerland. The logistic, environmental and public-acceptance issues raised by such a plant make the feasibility of installing a FT synthesis plant in Switzerland appear questionable from today's perspective. Because of this reason, we do not consider the FT plant as a feasible investment choice in the first two scenario sets. However, since the FT facility and the methanation plant have the potential to compete with each other, the FT plant is a possible choice of investment in the third set of scenarios in order to illustrate the competition between them.

Table 2: Overview of the scenarios examined in this study

Scenario Set Name	Scenario Description
Gas and Oil Price	The oil price increases from 28 US$/bbl in 2000 to *Scenario O1:* 100 US$/bbl *Scenario O2:* 110 US$/bbl *Scenario O3:* 120 US$/bbl *Scenario O4:* 130 US$/bbl in the year 2050. The gas price increases from 3.3 US$/GJ in the year 2000 in the same proportion.
Bio-SNG Subsidies	Subsidies on synthetic natural gas (bio-SNG) are set at *Scenario S1:* 6 US$/GJ (3.24 Rp/kWh) *Scenario S2:* 7 US$/GJ (3.78 Rp/kWh) *Scenario S3:* 8 US$/GJ (4.32 Rp/kWh) *Scenario S4:* 9 US$/GJ (4.86 Rp/kWh) *Scenario S5:* 10 US$/GJ (5.40 Rp/kWh). The oil price increases to 50 US$/bbl in 2050.
Gas and Oil Price & Bio-SNG Subsidies	The oil price increases between 70 and 80 US$/bbl in 2050 and the gas price increases accordingly. Subsidies of 4 US$/GJ to 5 US$/GJ (2.7 Rp/kWh) are placed on synthetic natural gas (bio-SNG). *Scenarios: F1 to F8: See Table 3 below for a detailed description of this set of scenarios*

4.1. Gas and Oil Price Scenarios

This section examines the effect on wood-based energy technologies of an increase in the gas and oil prices. We evaluate three scenarios, with different levels of oil and gas price increases. Important in this respect is that the oil price is assumed to be the driving force behind fossil resource prices. Hence, if the oil price increases, all other fossil resource prices increase proportionally. In the four scenarios, the oil prices increase from 28 US$/bbl in 2000 to 100 US$/bbl, 110 US$/bbl, 120 US$/bbl and 130 US$/bbl in the year 2050. The absolute values of the oil price for every scenario and year are displayed in Figure 13.

The reader should bear in mind that the oil price is a highly uncertain, volatile and unpredictable variable. However, recent trends in the global oil markets and industry indicate that there is a possibility of large oil price shocks materializing in the future due to either bottlenecks in oil supply or strong increases in demand (e.g. The Economist, 2005; IEA, 2005). The price levels chosen in the scenarios analyzed here are illustrative and do not represent the endorsement of any particular oil price projection by the authors. Using high oil prices in our modelling exercise help identify the technologies that could play a role in weaning the Swiss energy system away from oil dependence. These oil price values represent the threshold levels at which, under the assumptions outlined here in our perfect-foresight energy-system model, the methanation technology becomes competitive in the marketplace when supporting policy measures are not implemented.

Figure 14 to Figure 17 present the results of this scenario set for different levels of oil prices. In each figure, the use of wood (primary energy) by different wood technologies is displayed. Every wood technology described in the following results represents a technology documented in section 2. Important in this respect is that the current use of wood, which amounts to about 20 PJ or about 20 % of the total theoretical wood potential in Switzerland in the year 2000 is not reported in the results. In the year 2000, this use can be separated in single-room heating systems (27 % of the total), building heating systems (25 %), automatic firing (38 %) and special firing (9%) (BfE, 2001a). In the following analysis those conventional technologies currently used are limited by an upper "ceiling" and compete for the current wood use of 20 PJ. Hence, the technologies under investigation within the scope of this report (Figure 2 to Figure 4) compete for the remaining amount of wood, which adds up to at least 80 PJ.

Moreover, in this case it is easy to derive the percentage of the total wood potential in Switzerland that is converted to final energy carriers by each technology investigated within the scope of this study since the total theoretical wood potential is approximately 100 PJ (see Figure 7). Thus, if for instance 10 PJ of wood are converted in a methanation plant to bio-SNG and heat then about 10 % of the total wood potential is used by the methanation plant.

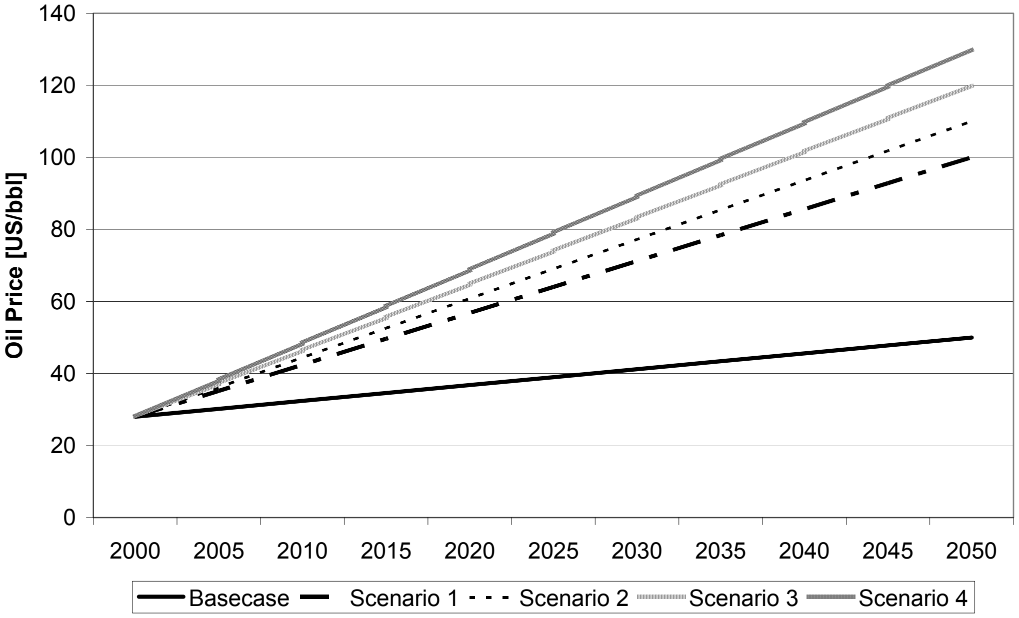

Figure 13: Oil prices in the Oil and Gas Price scenarios compared to the prices in the baseline scenario.

In Figure 14, the oil price reaches 100 US$/bbl in the year 2050 (scenario O1). At this level, the production of biomass-based heat and electricity in a Combined Heat and Power (CHP) plant is competitive in Switzerland. The first large (more than 2 MW) biomass CHP gasification plant is built in 2040. Thereafter the amount of wood converted to electricity and heat increases to about 7 PJ in the year 2050, which amounts to about 7 % of the total wood potential of Switzerland.

In Figure 15 the oil price reaches 110 US$/bbl in 2050 (scenario O2). The amount of wood used in CHP plants is, with about 20 PJ in 2050, much higher than in the previous case. The first investment is made earlier, in the year 2035. The bio-SNG plant has a small contribution in the last years of the time horizon and mainly in the residential sector.

An oil price of 120 US$/bbl in 2050 is reached in the case depicted in Figure 16 (scenario O3). In this scenario, the CHP plant starts to be competitive in 2025 and the methanation plant in 2045. The total amount of wood used increases substantially compared to the amount used in the previous scenarios discussed above. The amount of wood converted by CHP plants in 2050 increases slightly while the amount of wood used for bio-SNG production increases substantially compared to the previous scenario. Notice, furthermore, that only a very small share of bio-SNG is used in the residential sector and nearly the total amount of bio-SNG is used in the transport sector.

If the oil price increases more drastically, to 130 US$/bbl in the year 2050 (scenario O4), an even larger amount of wood is converted to heat and bio-SNG and the methanation plant starts to be competitive in the year 2040. In contrast, the output of the wood-based CHP plant is reduced. In the year 2050, about 70 PJ of wood is converted to heat and bio-SNG in the methanation plant and about 20 PJ of wood is converted to heat and electricity in the CHP plant. Notice that the bulk of the produced bio-SNG is used in the transport sector in this scenario, see Figure 17.

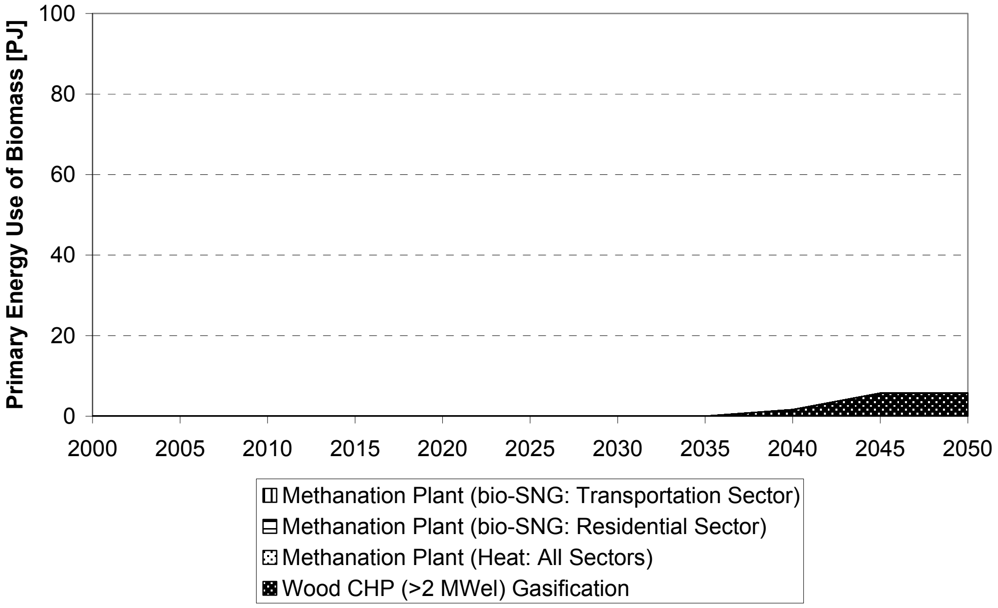

Figure 14: Primary energy use of wood by different technologies in the scenario O1. The oil price reaches 100 US$/bbl in 2050. The Fischer-Tropsch synthesis is not an investment option.

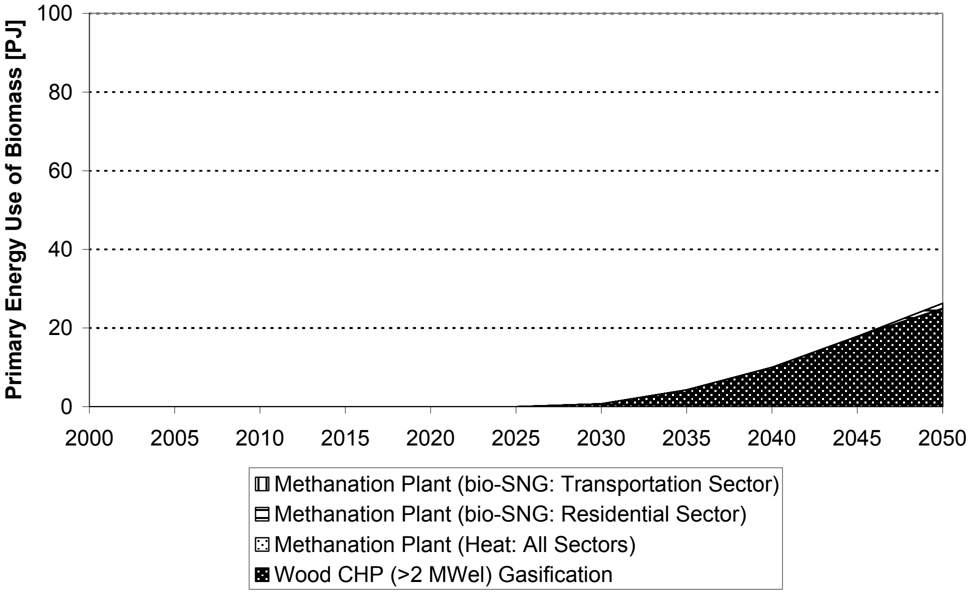

Figure 15: Primary energy use of wood by different technologies in the scenario O2. The oil price reaches 110 US$/bbl in 2050. The Fischer-Tropsch synthesis is not an investment option.

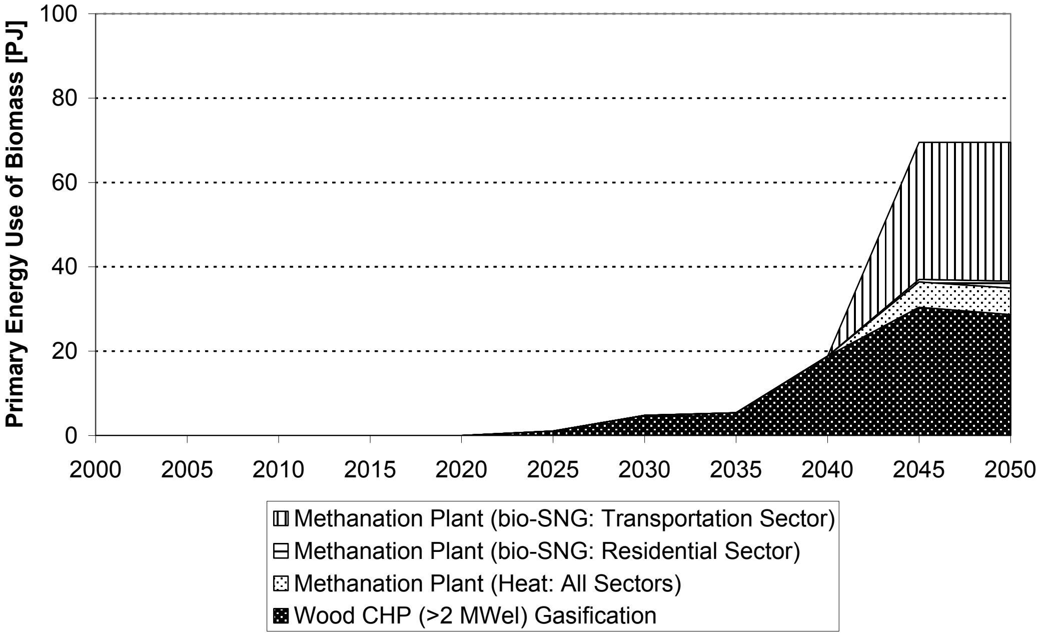

Figure 16: Primary energy use of wood by different technologies in the scenario O3. The oil price reaches 120 US$/bbl in 2050. The Fischer-Tropsch synthesis is not an investment option.

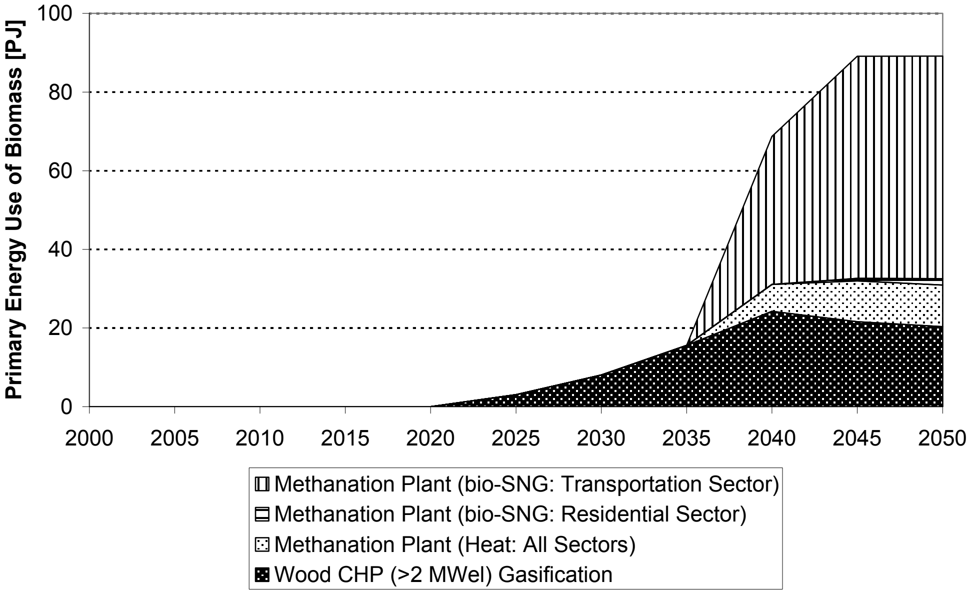

Figure 17: Primary energy use of wood by different technologies in the scenario O4. The oil price reaches 130 US$/bbl in 2050. The Fischer-Tropsch synthesis is not an investment option.

The figures suggest that when a specific oil price is reached in a given scenario the bio-SNG plant becomes competitive in the Swiss energy market. In order to find out this threshold, we examine the year of the first market penetration in a given scenario and take the corresponding oil price for this year. In Figure 15 the threshold is 110 US$/bbl, in Figure 16 it is 110.9 and in Figure 17 it is 109.8 US$/bbl. Thus, given the case that bio-SNG is not subsidized, all model scenario runs confirm an oil price threshold of about 110 US$/bbl. That is, it would be necessary to exceed this oil price threshold for the methanation plant to become competitive with conventional energy conversion technologies if no other supporting policy measures are implemented.

Figure 18 presents a summary of the results analyzed in this section. In the figure the primary energy use of biomass for the final year of the modeling horizon, 2050, in all scenarios (O1 to O4) is displayed.

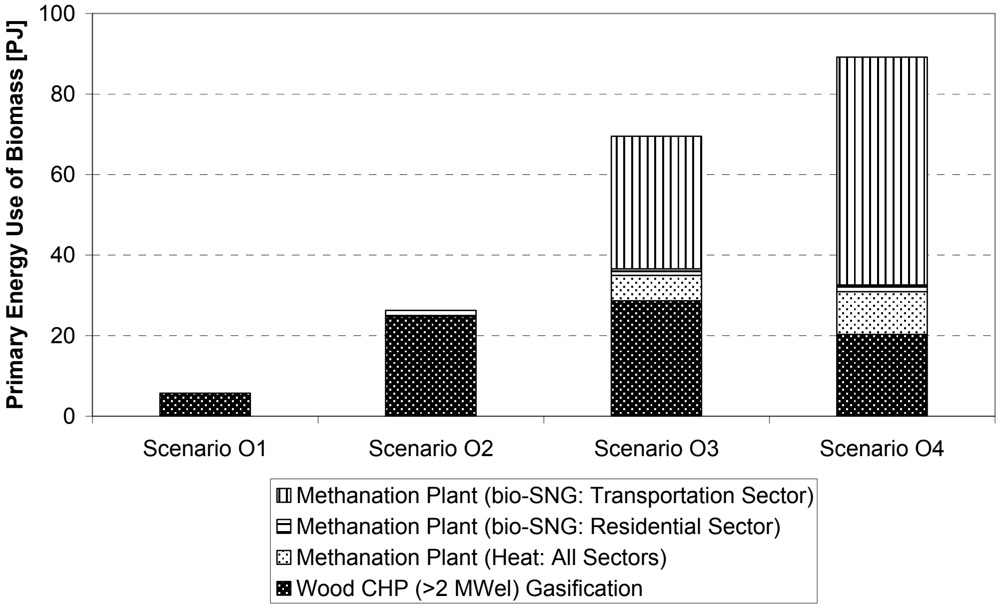

Figure 18: Primary energy use of biomass by different technologies in all Gas and Oil Price scenarios in the year 2050. The Fischer-Tropsch synthesis is not an investment option.

Figure 19 depicts the total CO_2 emissions of the energy system in Switzerland in the year 2050 for different scenarios. The first column on the left of the figure represents the baseline emissions, which amount to 52 Mt CO_2, and all other columns to the left show the emissions of the scenarios analyzed in this section. On average, the emissions are about 38 Mt CO_2 or 27 % lower than the emissions of the baseline scenario. Furthermore, one can observe slightly decreasing CO_2 emissions for an oil price increase from 100 to 130 US$/bbl (scenarios O1 to O4) in 2050. The major CO_2 reduction, however, is taking place for the oil price increase from the baseline price of 50 US$/bbl to the O1 scenario price of 100 US$/bbl.

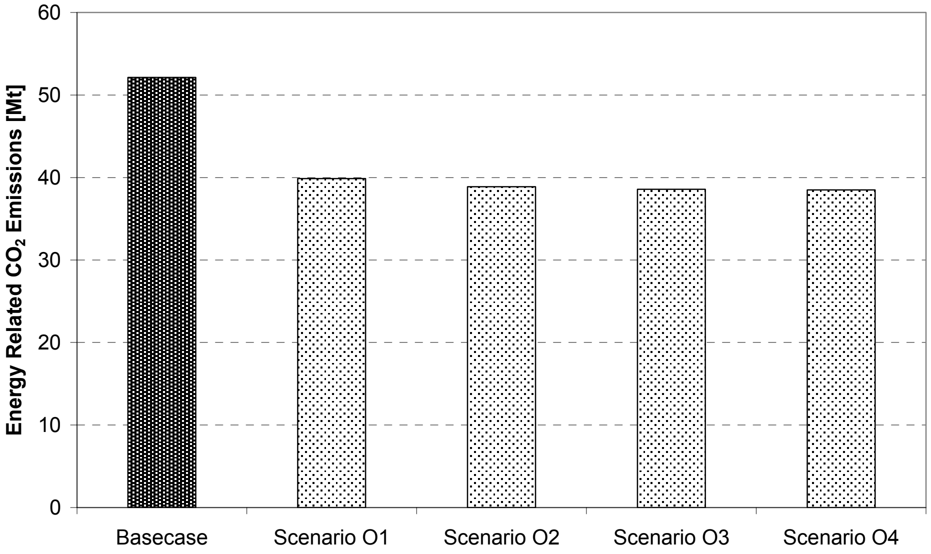

Figure 19: Energy-related CO_2 emissions in Switzerland in the Gas and Oil Price scenarios (O1 to O4) for the year 2050.

Two main factors influence the reduction in CO_2 emissions, namely fuel switching to cleaner fuels and investments in more efficient technologies. We illustrate their influence by taking a closer look at the transportation sector. Figure 20 shows the final energy consumption by fuel in the transportation sector in the year 2050 for the scenario O3, where the oil price reaches 120 US$/bbl in the year 2050. In the scenario O3, the total final energy consumption in the transportation sector adds up to approximately 400 PJ in 2050. Compared to the baseline scenario, with a final energy consumption of 445 PJ in the transportation sector in 2050, an efficiency increase of about 10 % is achieved. Moreover, the figure also points out the fuel switching that is taking place compared to the baseline scenario. Oil products dominate the final-energy mix in the transportation sector in the baseline scenario and virtually no gaseous energy carriers (natural gas or bio-SNG) are consumed (see Figure 12 above). In the scenario O3, this the combined share of natural gas and bio-SNG grows significantly. This is interesting because both fuels are distributed via the same gas pipeline, thus exploiting synergies related to the transport infrastructure.

The increase in the participation of natural gas and bio-SNG in the final-energy mix is mainly driven by the introduction of gas-powered cars in the passenger car subsector.[9] While most of the gas burnt in the gas-powered cars is natural gas, a small but noticeable fraction is bio-SNG.

More generally, under the assumptions in this set of scenarios, with the increase of oil and gas prices to the levels of the scenario O1 and O2, natural gas substantially increases its role in the transport sector. With the further increase in oil and natural gas prices in scenarios O3 to O4, a fraction of this natural gas is replaced by bio-SNG.

These results illustrate the potential synergies that could exist between bio-SNG and natural gas. Specifically, the development of an infrastructure for transmission and distribution of natural gas and the promotion of the introduction of gas-based technologies in the transport sector could be beneficial for the introduction of bio-SNG. In its turn, bio-SNG could contribute to a hedging strategy against substantial oil and gas price increases and, by reducing CO_2 emissions, to the “greening” of natural gas.

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[9] For an analysis of the conditions under which gas-powered vehicles could penetrate the Swiss market see Janssen (2005) and Janssen *et al.* (2005).

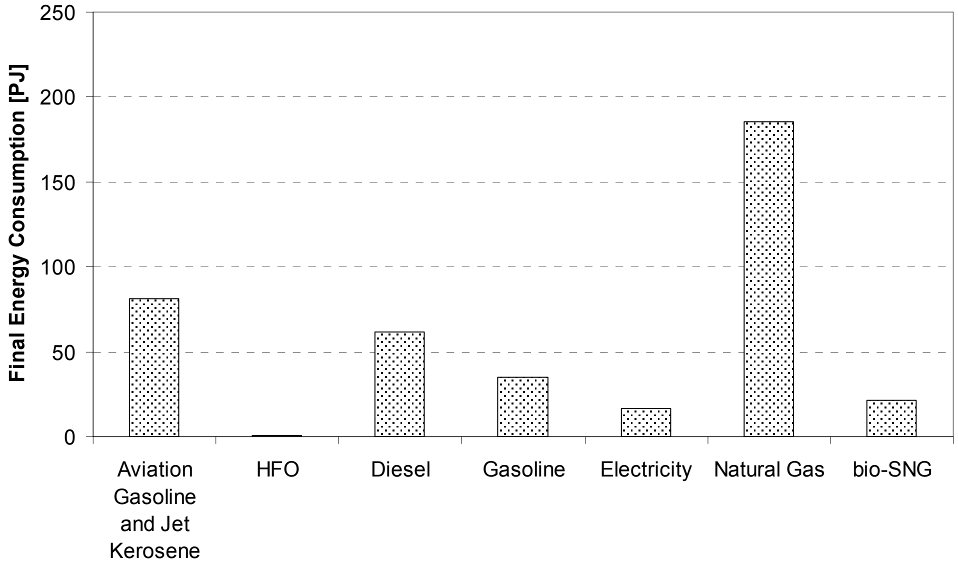

Figure 20: Final energy consumption by fuel of the transport sector in the year 2050 for the scenario O3. In the O3 scenario, the oil price reaches 120 US$/bbl in the year 2050.

Based on these results, the following conclusions can be drawn:

1) If the oil price increases to 100 US$/bbl in 2050, CHP plants are competitive with other conventional energy conversion technologies in Switzerland.
2) If the oil price reaches 100 US$/bbl or more, wood-based methanation plants, which produce bio-SNG and heat, are competitive in Switzerland.
3) The higher the oil price the earlier wood technologies are competitive and the more wood is converted to bio-SNG and heat.
4) The produced bio-SNG is primarily used in the transportation sector. The use of bio-SNG in the residential sector is very limited. This is because the residential sector offers cheaper options to compensate for a high oil price. These options could be, for instance, energy-saving houses or other more efficient conventional heating technologies. In contrast, the transportation sector offers fewer options to compensate for the high oil price. This is the reason why bio-SNG is used largely in this sector when the oil price reaches higher levels.
5) An increasing oil price results, on the one hand, in investments in technologies that are more efficient and, on the other hand, in fuel switching to cleaner fuels. In return, this implies that CO_2 emissions are reduced significantly.

4.2. Bio-SNG Subsidies Scenarios

The scenario set discussed in this section consists of five different scenarios. Each scenario has a different subsidy level on synthetic natural gas from wood (bio-SNG). The scenarios allocate subsidies of 6 US$/GJ (3.24 Rp/kWh), 7 US$/GJ (3.78 Rp/kWh), 8 US$/GJ (4.32 Rp/kWh), 9 US$/GJ (4.86 Rp/kWh) and 10 US$/GJ (5.40 Rp/kWh), respectively. In each of the scenarios, the subsidies are held constant over the whole time horizon. As mentioned in chapter 3.1 the model does not include taxes. Hence, the subsidies can be interpreted as a tax exemption for bio-SNG. The oil price in each of the scenarios examined in this section increases from 29 US$/bbl in the year 2000 to 50 US$/bbl in the year 2050, just as in the baseline scenario.

Figure 21 to Figure 25 display the results of this set of scenarios. In each figure, the primary energy use of wood by different wood technologies is presented. With the level of subsidies allocated to bio-SNG in these scenarios, only the methanation plant becomes competitive and no other technologies penetrate the market. As indicated before, the methanation plant produces heat with an efficiency of 10% and bio-SNG with an efficiency of 55%. In relation to that, the results indicate how much wood is used for the production of heat and bio-SNG. The figures also show in which sectors the produced bio-SNG is used.

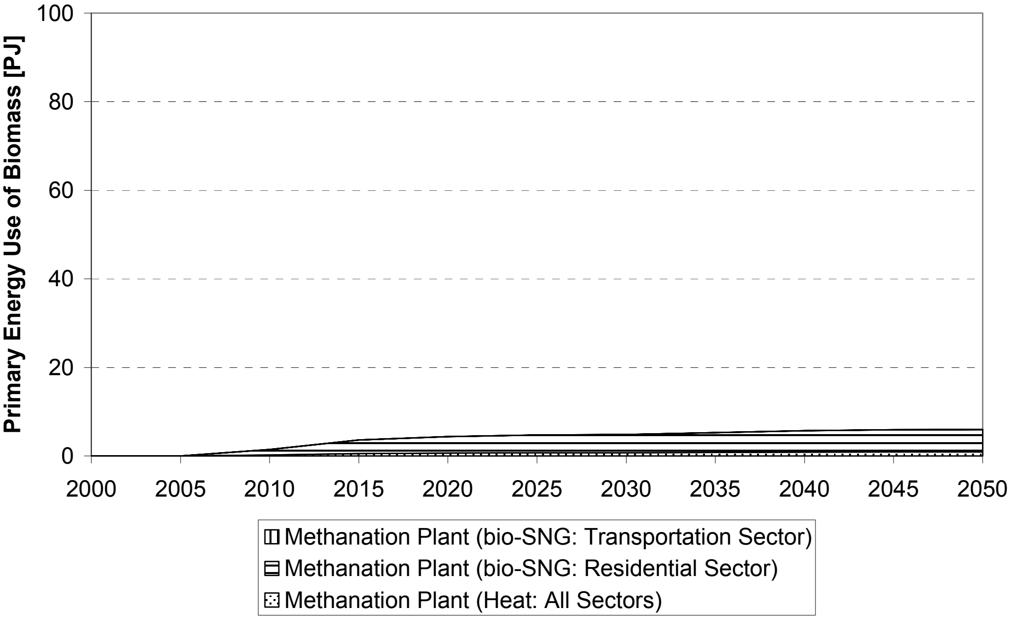

Figure 21: Primary energy use of wood by different technologies in the scenario S1. A subsidy of 6 US$/GJ (3.24 Rp/kWh) is allocated to bio-SNG. The Fischer-Tropsch synthesis is not an investment option.

Figure 21 depicts the results if subsidies of 6 US$/GJ (3.24 Rp/kWh) are allocated to bio-SNG. In the year 2015 bio-SNG becomes competitive but grows over time only slightly. In 2050 a total of 6 PJ of wood is transformed to bio-SNG and heat, which corresponds to about 6 % of the countrywide wood potential. Remarkable is that the total amount of bio-SNG produced is used in the residential sector where it replaces natural gas.

Figure 22 and Figure 23 depict the primary energy use of biomass for the scenarios S2 and S3 with a subsidy allocation of 7 US$/GJ (3.78 Rp/kWh) and 8 US$/GJ (4.32 Rp/kWh) respectively. A total wood consumption of about 36 PJ and 40 PJ respectively is reached in 2050 and the total bio-SNG produced is used in the residential sector. Being nearly identical, the figures show that an upper bound for substituting natural gas with bio-SNG in heating systems in the household sector exists. This substitution is limited, which is the reason why the figures look alike despite the increasing subsidies. Moreover, the produced bio-SNG is still not cheap enough to be competitive in other end-use sectors such as the transportation sector, as illustrated in the next figure.

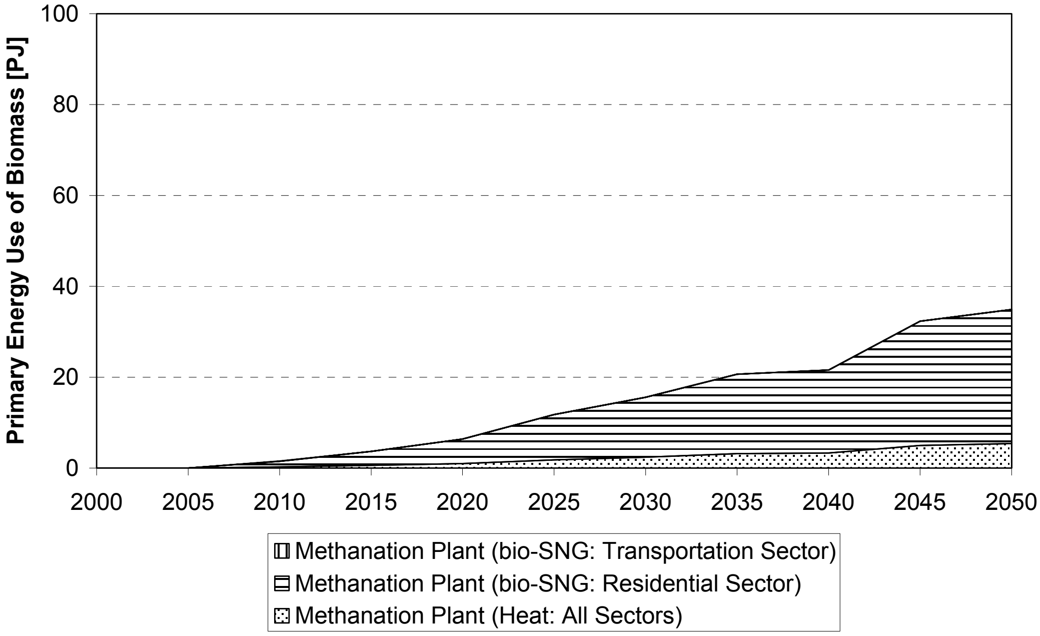

Figure 22: Primary energy use of wood by different technologies in the scenario S2. A subsidy of 7 US$/GJ (3.78 Rp/kWh) is allocated to bio-SNG. The Fischer-Tropsch synthesis is not an investment option.

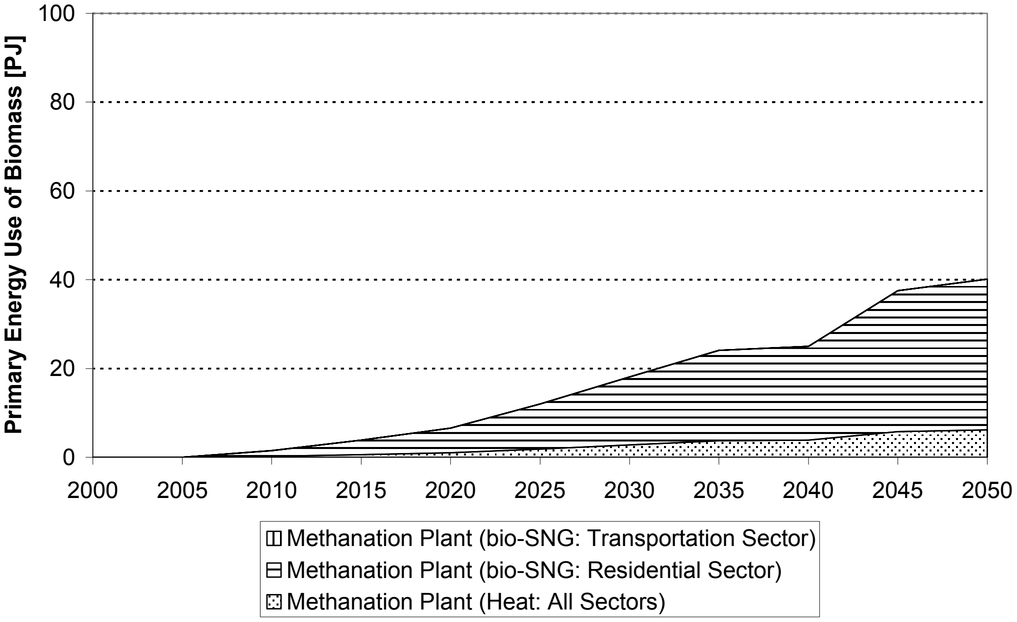

Figure 23: Primary energy use of wood by different technologies in the scenario S3. A subsidy of 8 US$/GJ (4.32 Rp/kWh) is allocated to bio-SNG. The Fischer-Tropsch synthesis is not an investment option.

Figure 24 and Figure 25 illustrate the primary energy use of biomass for the scenarios S4 and S5 when the subsidies increase to 9 US$/GJ (4.86 Rp/kWh) and 10 US$/GJ (5.40 Rp/kWh) respectively. The amount of bio-SNG used in the residential sector remains approximately constant. However, the total amount of wood transformed to bio-SNG and heat increases. In 2050, 50 PJ and 70 PJ of wood respectively are converted, amounting to about 50 % and 70 % of the total wood potential respectively. In the residential sector bio-SNG basically replaces ordinary natural gas. However, the subsidies are high enough to increase the competitiveness of bio-SNG beyond the residential sector, which exhibits a limited potential for penetration, and bio-SNG is used in the transportation sector, which offers a larger potential for this energy carrier. With this level of subsidy and under the assumptions outlined in this study, natural gas cars become competitive and replace conventional fuel cars in Switzerland.

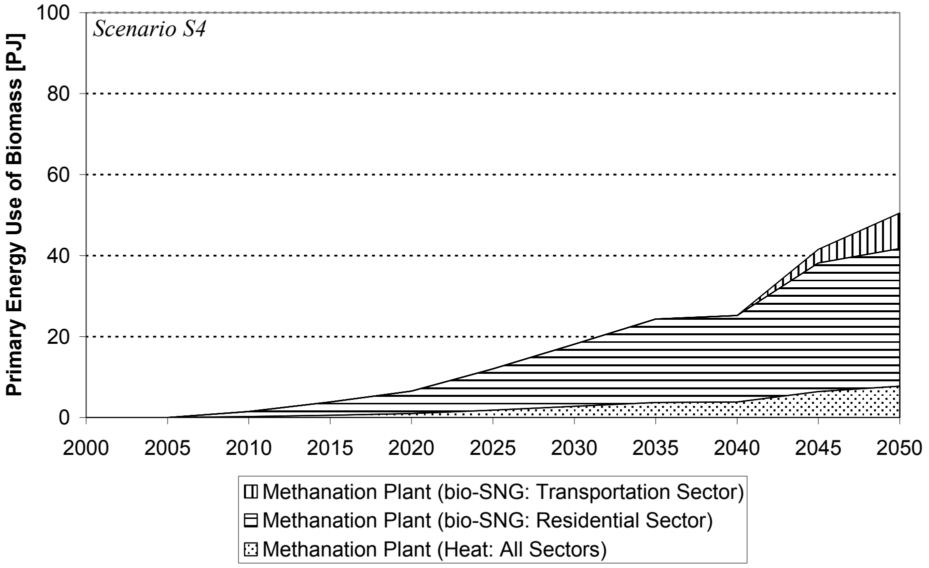

Figure 24: Primary energy use of wood by different technologies in the scenario S4. A subsidy of 9 US$/GJ (4.86 Rp/kWh) is allocated to bio-SNG. The Fischer-Tropsch synthesis is not an investment option.

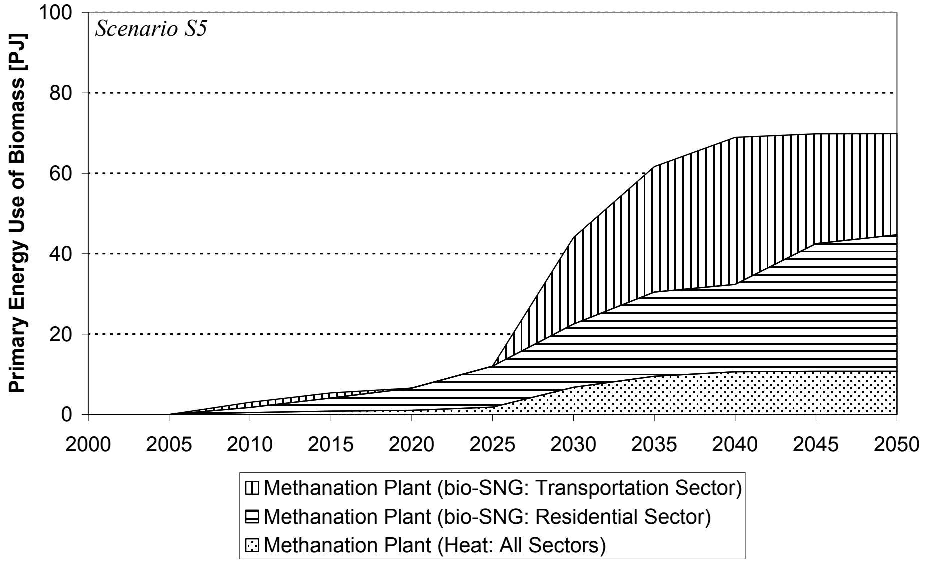

Figure 25: Primary energy use of wood by different technologies in the scenario S5. A subsidy of 10 US$/GJ (5.40 Rp/kWh) is allocated to bio-SNG. The Fischer-Tropsch synthesis is not an investment option.

Figure 26 presents a summary of the results analyzed in this section. In the figure, the primary-energy consumption of wood for the final year of the modeling horizon, 2050, of all scenarios (S1 to S5) is displayed. As explained before, increasing levels of subsidies result in an increasing use of the methanation plant. However, only with high levels of subsidies does bio-SNG play a role in the transportation sector.

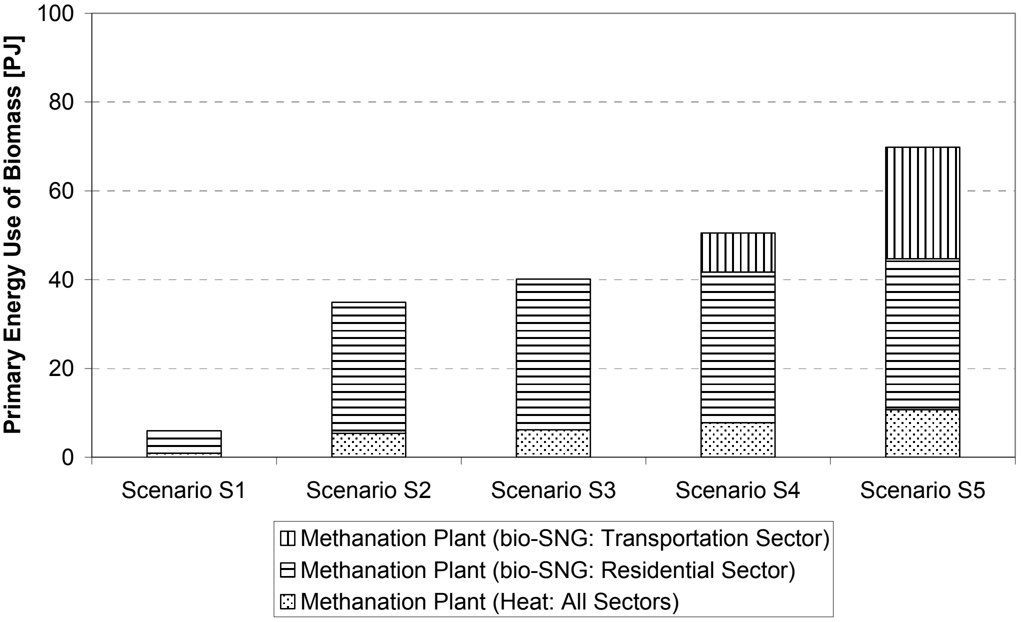

Figure 26: Primary energy use of wood in all bio-SNG Subsidy scenarios (S1 to S5) in the year 2050. The Fischer-Tropsch synthesis is not an investment option.

The model determines the solution based on cost minimization. Therefore, one can verify the results by performing independent and simplified spreadsheet calculations concerning the production cost and determine the competitiveness of technologies in the markets. For example, using a wood price of 4 Rp/kWh and the assumptions shown in Appendix 2, we conclude that methane can be produced for 12.36 Rp/kWh. Subtracting subsidies of about 5 Rp/kWh from that cost leads to a competitive technology with a production cost of 13.63 US$/GJ, and this in turn, confirms the model results presented in this section. This simplified spreadsheet calculation does not account for possible revenues of by-production (i.e., heat in our example) but this can be further improved to get a more realistic cost estimate of methanation.

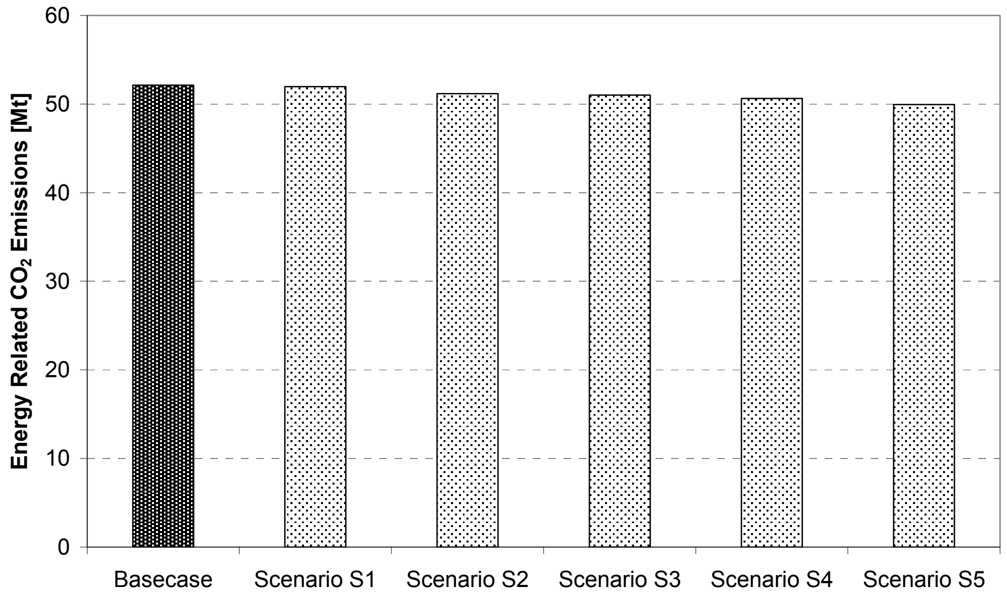

Figure 27: Energy-related CO_2 emissions in Switzerland in the Bio-SNG Subsidy scenarios (S1 to S5) for the year 2050.

Although, in the best case, the total CO_2 emissions are reduced by about 2 Mt or 4 % in 2050 in the bio-SNG subsidy scenarios, a mere allocation of subsidies on bio-SNG does not influence the reduction of CO_2 emissions significantly. This is reflected in the transportation sector, which has the largest contribution to CO_2 emissions in the year 2050. In the scenarios S4 and S5, respectively, about 5.7 PJ and 16.3 PJ of final energy are supplied by bio-SNG. However, because the oil and gas prices remain at the same levels of the baseline scenario, natural gas does not play a major role in the transportation sector in the bio-SNG subsidy scenarios. Hence, the role of gas (bio-SNG and natural gas) in the transport sector remains smaller than in the Gas and Oil Price scenarios. In the scenario S5, about 3.7 % of the final energy in the transportation sector is supplied by bio-SNG.

This behavior is illustrated by Figure 28, which presents the final energy consumption by fuel in the transport sector in the year 2050 for the scenario S5, where a subsidy of 10 US$/GJ (5.40 Rp/kWh) is allocated to bio-SNG. In this scenario, oil products still dominate the transport sector towards the end of the time horizon, natural gas does not penetrate the market and the contribution of subsidized bio-SNG, although noticeable, is not enough to produce substantial changes in the final-energy mix. Consequently, CO_2 emissions from this sector remain high.

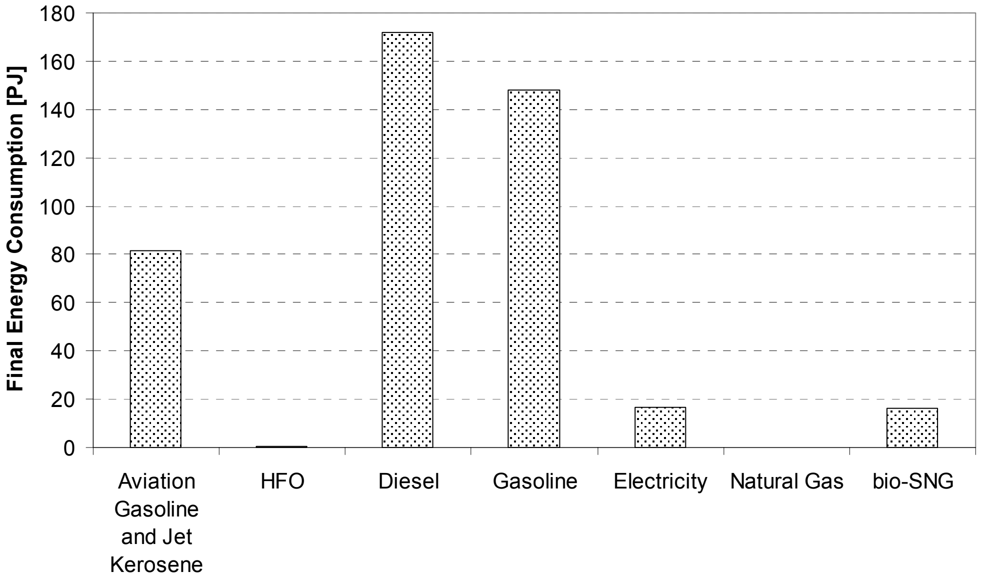

Figure 28: Final energy consumption by fuel of the transport sector in the year 2050 for the scenario S5, where a subsidy of 10 US$/GJ (5.40 Rp/kWh) is allocated to bio-SNG.

Thus, although the subsidies support a substantial increase in the production of bio-SNG, from the perspective of the Swiss energy system as a whole this increase is not enough by itself to produce a noticeable reduction of CO_2 emissions. In contrast, and as it was seen in the previous set of scenarios (Gas and Oil Price scenarios), the combined use of natural gas and bio-SNG in the transport sector can lead to a significant reduction of CO_2 emissions.

Based on these results the following conclusions can be drawn:

1) If subsidies on bio-SNG plants are relatively small, 6 US$/GJ (3.24 Rp/kWh) or more, bio-SNG substitutes fossil natural gas in the residential sector. However, the replacement of natural gas in the residential sector is limited.
2) If the subsidies increase to about 9 US$/GJ (4.86 Rp/kWh) or more, bio-SNG becomes competitive in the transportation sector. This sector has a very large potential to substitute conventional cars by cars fuelled with bio-SNG. The upper limit of the potential seems to be the availability of wood. However, despite the fact that the total amount of bio-SNG is relatively high, the share of gas (bio-SNG and natural gas) remains small.
3) The total CO_2 emissions are reduced slightly, by about 4 % in the best case.

4.3. Gas and Oil Price & Bio-SNG Subsidy Scenarios

The scenario set examined in this section (Gas and Oil Price & Bio-SNG Subsidy) combines the two previous sets of scenarios. This is achieved, on the one hand, by increasing the oil price to values between 70 and 80 US$/bbl in 2050 and, on the other hand, by allocating subsidies on bio-SNG between 4 US$/GJ (2.16 Rp/kWh) and 5 US$/GJ (2.7 Rp/kWh). In this respect, the scenario set assumes less drastic changes in the oil price development and lower subsidies on methanation plants compared to the scenario sets described in sections 4.1 and 4.2. All other assumptions remain the same.

We divide the set of scenarios under consideration in this section into three distinct subgroups, according to the way Fischer-Tropsch (FT) plants are implemented in the model (see Table 3). The subgroups of scenarios differ from each other regarding the presence/absence and modality (single product or co-production) of the Fischer-Tropsch facility in each of them. A first scenario type (F1 to F4) evaluates the results if no FT plant is implemented in the model. The second (F5 and F6) and third (F7 and F8) scenario types assume that investments can be made in FT plants. In the second scenario type, however, a FT plant produces the main product FT liquids and the by-product electricity. That is, the FT plant is a co-production facility. The third scenario type assumes that a FT plant produces only the main product FT liquids and no by-product. In all previous sections, the FT plant was not permitted to be invested in.

Table 3: Parameters modified for the sensitivity analysis of the Gas and Oil Price & Bio-SNG Subsidy scenarios.

Scenario Families Analyzed in this Section		
Fischer-Tropsch synthesis is not an investment option	Fischer-Tropsch synthesis is an investment option. The products are Fischer-Tropsch diesel and electricity	Fischer-Tropsch synthesis is an investment option. The product is only Fischer-Tropsch diesel
Scenario F1 Oil Price: 70 US$/bbl Subsidy: 4 US$/GJ		
Scenario F2 Oil Price: 70 US$/bbl Subsidy: 5 US$/GJ	*Scenario F5* Oil Price: 70 US$/bbl Subsidy: 5 US$/GJ	*Scenario F7* Oil Price: 70 US$/bbl Subsidy: 5 US$/GJ
Scenario F3 Oil Price: 80 US$/bbl Subsidy: 4 US$/GJ	*Scenario F6* Oil Price: 80 US$/bbl Subsidy: 4 US$/GJ	*Scenario F8* Oil Price: 80 US$/bbl Subsidy: 4 US$/GJ
Scenario F4 Oil Price: 80 US$/bbl Subsidy: 5 US$/GJ		

Figure 29 to Figure 32 illustrate the results of the scenarios if investments in FT plants are not optional. In this case the first investments on bio-SNG plants become competitive in the Swiss energy market if the oil price increases only to 70 US$/bbl in 2050 and if subsidies on bio-SNG are as low as 4 US$/GJ (2.16 Rp/kWh), see Figure 29. However, despite the fact that investments in the methanation plant start already in the year 2025 the production of bio-SNG is small and only about 6 PJ of wood are converted to bio-SNG in the year 2050.

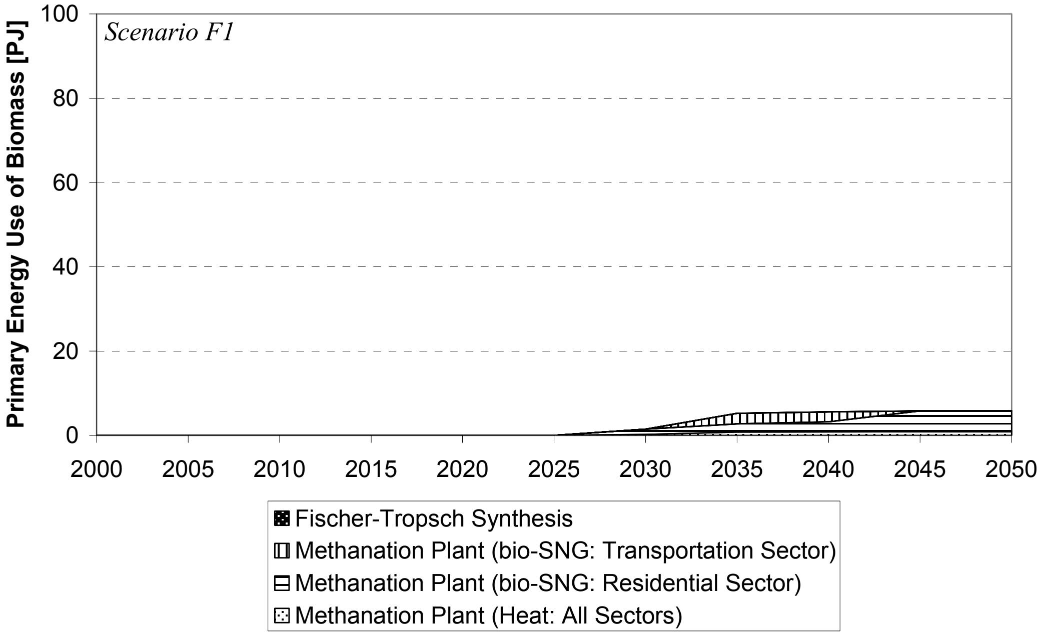

Figure 29: Primary energy use of wood by different technologies in the scenario F1. The oil price reaches 70 US$/bbl in 2050 and subsidies on bio-SNG amount to 4 US$/GJ (2.16 Rp/kWh). The Fischer-Tropsch synthesis is not an investment option.

Figure 30 and Figure 31 illustrate the use of wood if the oil price increases to 70 US$/bbl and 80 US$/bbl respectively in 2050 and if the subsidies on bio-SNG reach 4 US$/GJ (2.16 Rp/kWh) and 5 US$/GJ (2.7 Rp/kWh) respectively. The two scenarios have a very similar outcome. In each scenario, the use of wood in the methanation plant increases drastically compared to the last scenario and the first investments are made earlier. Moreover, it is important to notice that most of the bio-SNG produced is used in the transportation sector.

Subsidies of 5 US$/GJ (2.7 Rp/kWh) and an oil price of 80 US$/bbl in the year 2050 are realized in Figure 32. In this case, more than 85 % of the produced bio-SNG is used in the transportation sector. Bio-SNG in the transportation sector substitutes conventional fuel cars such as diesel and gasoline cars whereas the amount of gas driven cars increases proportionally. Moreover, compared to the previous scenarios of this section, very significant investments in the methanation plant start in the year 2020.

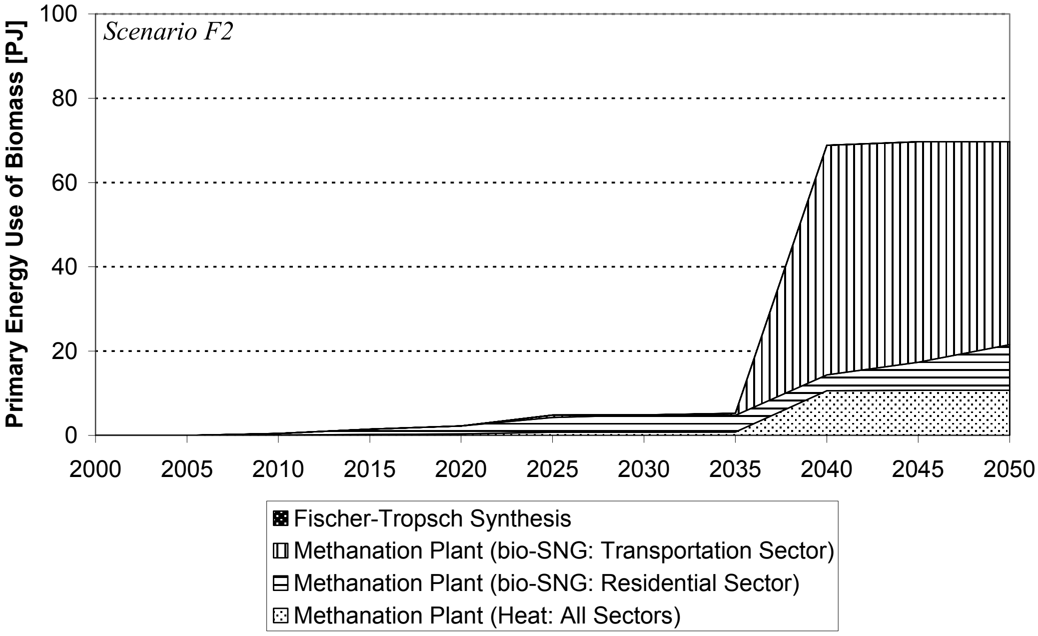

Figure 30: Primary energy use of wood by different technologies in the scenario F2. The oil price reaches 70 US$/bbl in 2050 and subsidies on bio-SNG amount to 5 US$/GJ (2.7 Rp/kWh). The Fischer-Tropsch synthesis is not an investment option.

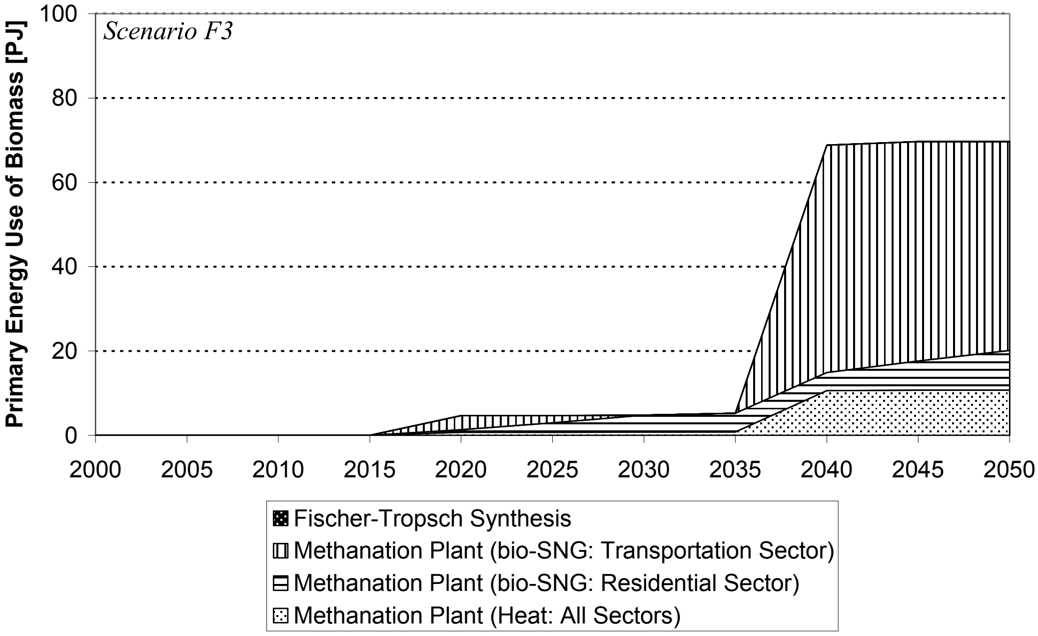

Figure 31: Primary energy use of wood by different technologies in the scenario F3. The oil price reaches 80 US$/bbl in 2050 and subsidies on bio-SNG amount to 4 US$/GJ (2.16 Rp/kWh). The Fischer-Tropsch synthesis is not an investment option.

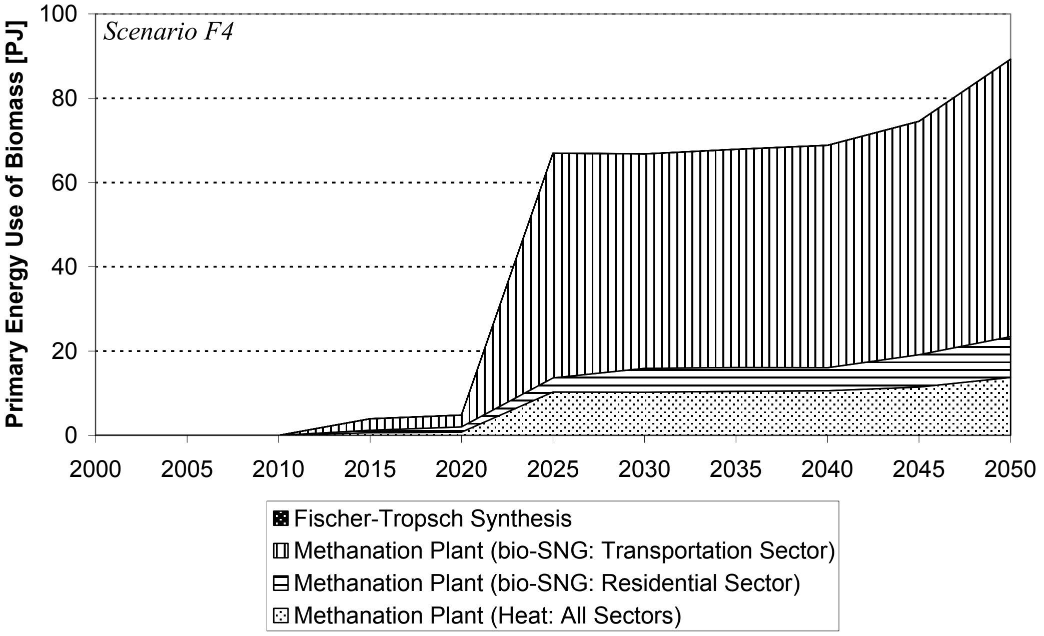

Figure 32: Primary energy use of wood by different technologies in the scenario F4. The oil price reaches 80 US$/bbl in 2050 and subsidies on bio-SNG amount to 5 US$/GJ (2.7 Rp/kWh). The Fischer-Tropsch synthesis is not an investment option.

Figure 33 presents a summary of the primary energy use of wood in the Gas and Oil Price & Bio-SNG Subsidy scenarios F1 to F4 for the year 2050. As can be seen, with the oil price and subsidy level in scenario F1 the contribution of the bio-SNG plant remains small. Increasing the level of subsidy (scenario F2) or the oil price (scenario F3) results in a larger introduction of bio-SNG particularly in the transportation sector. A simultaneous increase of both oil price and subsidy levels (scenario F4) augments the production of bio-SNG further.

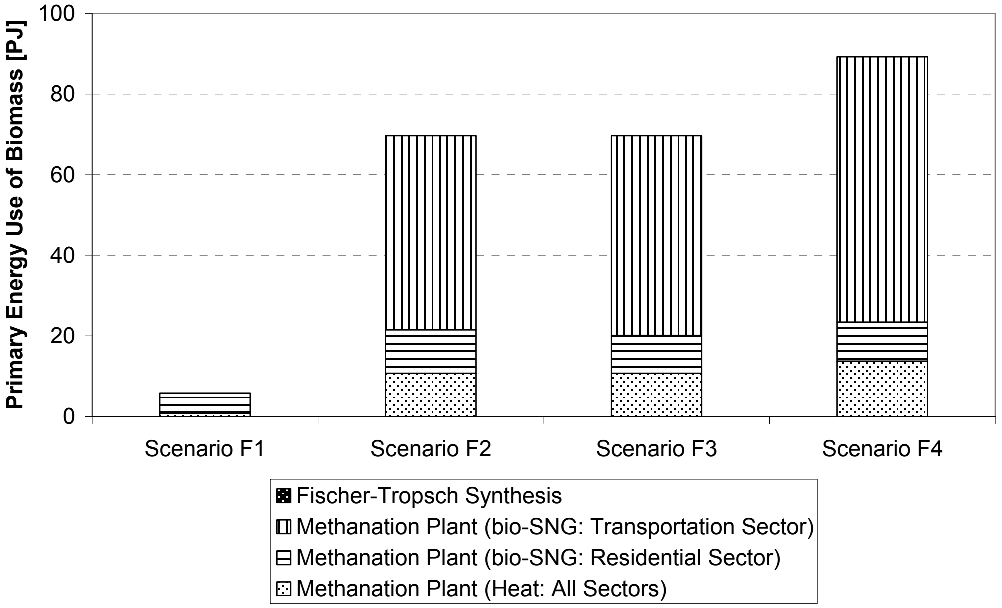

Figure 33: Primary energy use of wood in the Gas and Oil Price & Bio-SNG Subsidy scenarios F1 to F4 for the year 2050.

Figure 34 and Figure 35 illustrate the results assuming a Fischer-Tropsch (FT) plant is a feasible investment possibility and can co-produce electricity (scenarios F5 and F6). In order to give an adequate comparison to the previous case, the oil price increases to 70 and 80 US$/bbl respectively. The subsidies to bio-SNG remain at 4 US$/GJ (2.16 Rp/kWh) and 5 US$/GJ (2.7 Rp/kWh) respectively. In these cases, the model takes full advantage of the FT plant. Only in scenario F5, the methanation plant plays a minor role (see Figure 34 below). However, this is only possible because the by-product electricity is dispatched to the Swiss electrical grid and can be sold to consumers, thus improving the economics of the FT plant. Moreover, although the bio-SNG plant also operates in a co-production mode, electricity can be sold at higher prices, compared to the heat co-produced by the bio-SNG plant. Therefore, the Fischer-Tropsch facility is the preferred investment choice in these two scenarios. Because of the large amount of FT liquids, the amount of diesel cars in the transport sector increases and the share of conventional gasoline cars drops significantly.

Despite the fact that these scenarios clearly favor the FT synthesis, in reality there could be a strong competition between the FT synthesis and the methanation plant. While many other factors may influence such competition, the possibility of operating these plants as co-production facilities and the relative attractiveness of the co-product in the market would play an important role. We illustrate this with the scenario analysis where the FT plant only produces FT liquids and the by-product electricity cannot be dispatched to the electrical grid (see Figure 36 and Figure 37 below). These results are the same as the results of first scenario set, Figure 30 and Figure 31. This time, despite the fact that the FT plant is a possible investment choice, the model rather invests in methanation plants. Again, most of the bio-SNG produced is used in the transportation sector to substitute conventional fuels. When examining the competitiveness of the FT plant and the methanation plant, it should be noticed that a methanation plant with a capacity of 100 MW could also be built as a cogeneration plant that produces electricity. Consequently, a methanation plant with the by-product electricity has a better chance to penetrate the energy market than a methanation plant with the by-product heat. Moreover, the competitiveness of the bio-SNG plant compared to the FT plant would also be increased.

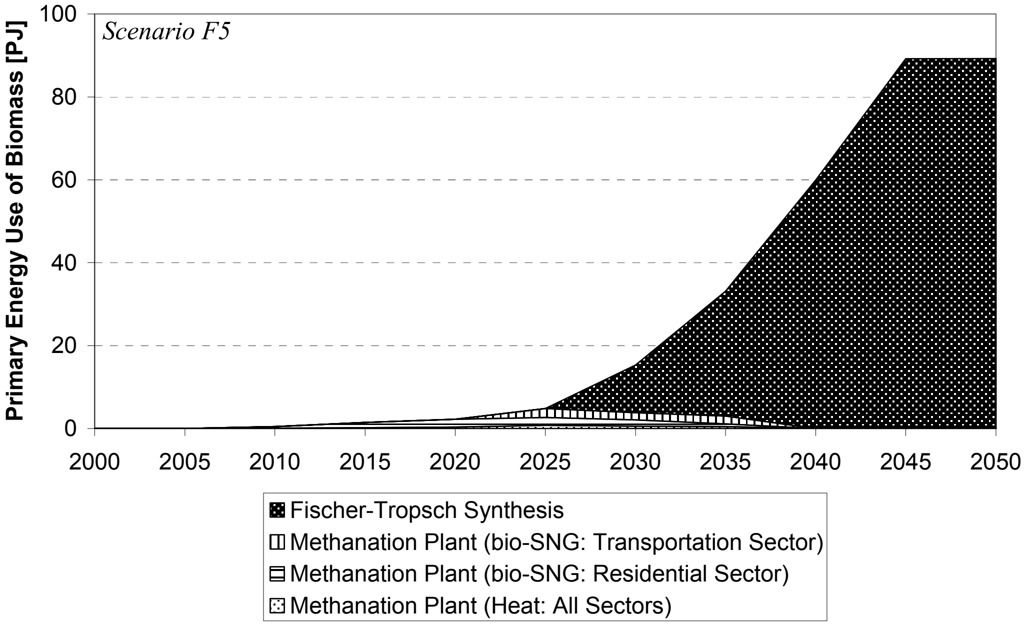

Figure 34: Primary energy use of wood by different technologies in scenario F5. The oil price reaches 70 US$/bbl in 2050 and subsidies on bio-SNG amount to 5 US$/GJ (2.7 Rp/kWh). The Fischer-Tropsch synthesis is an investment option and produces FT liquids and the by-product electricity.

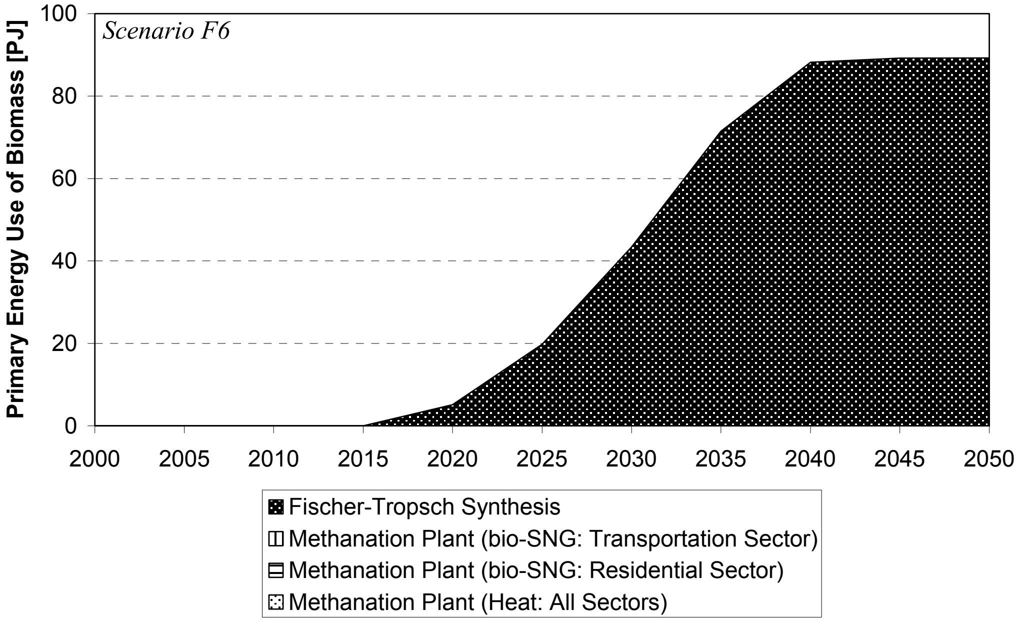

Figure 35: Primary energy use of wood by different technologies in scenario F6. The oil price reaches 80 US$/bbl in 2050 and subsidies on bio-SNG amount to 4 US$/GJ (2.16 Rp/kWh). The Fischer-Tropsch synthesis is an investment option and produces FT liquids and the by-product electricity.

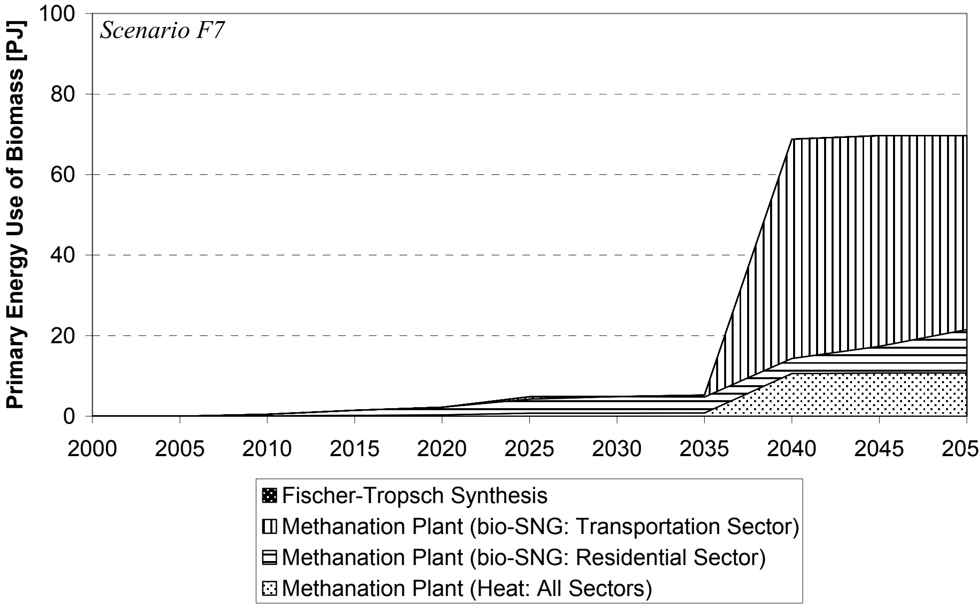

Figure 36: Primary energy use of wood by different technologies in the scenario F7. The oil price reaches 70 US$/bbl in 2050 and subsidies on bio-SNG amount to 5 US$/GJ (2.7 Rp/kWh). The Fischer-Tropsch synthesis is an investment option and produces FT liquids but not the by-product electricity.

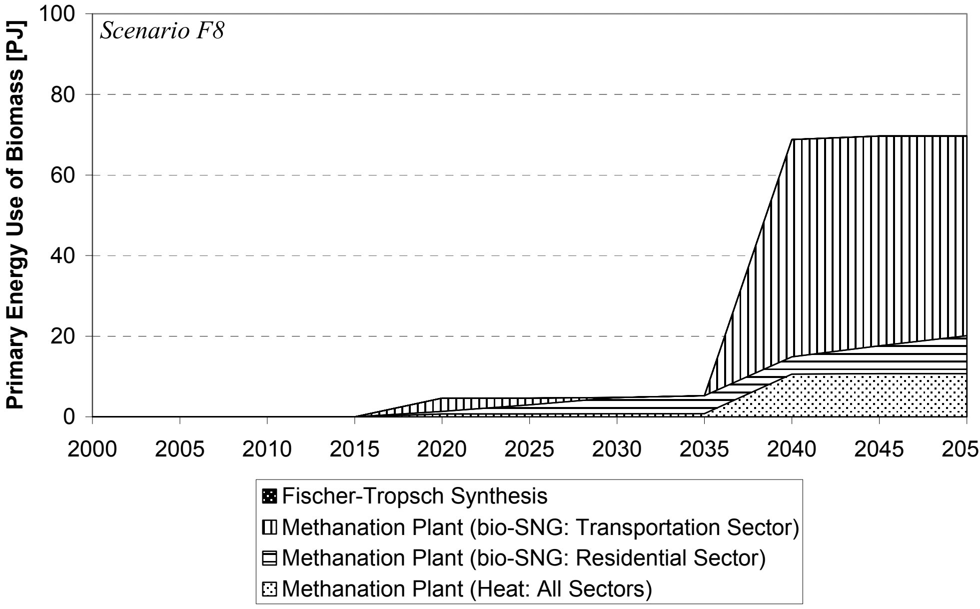

Figure 37: Primary energy use of wood by different technologies in the scenario F8. The oil price reaches 80 US$/bbl in 2050 and subsidies on bio-SNG amount to 4 US$/GJ (2.16 Rp/kWh). The Fischer-Tropsch synthesis is an investment option and produces FT liquids but not the by-product electricity.

Figure 38 presents a summary of the primary energy use of wood in the scenarios F5 to F8 for the final year of the modeling horizon (2050). As can be seen, under the assumptions outlined here, if the Fischer-Tropsch facility can co-produce electricity, it becomes more competitive than the bio-SNG plant. If, however, the Fischer-Tropsch facility is only allowed to produce FT liquids, the bio-SNG plant is more attractive.

These results point out the fact that a biomass-based facility producing only electricity could be an attractive option under the assumptions outlined in this set of scenarios.

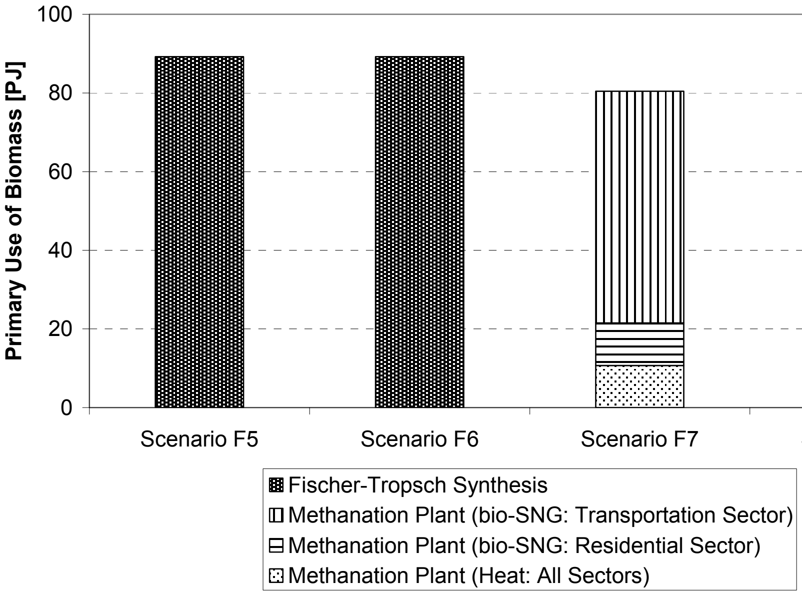

Figure 38: Primary energy use of the Gas and Oil Price & Bio-SNG Subsidy scenarios F5 to F8 in the year 2050. In scenarios F5 and F6, the Fischer-Tropsch facility is allowed to co-produce electricity. In scenarios F7 and F8, the Fischer-Tropsch facility only produces Fischer-Tropsch liquids.

Figure 39 and Figure 40 show the total CO_2 emissions of the Gas and Oil Price & Bio-Subsidy scenarios. With average emissions of about 42 Mt CO_2, this scenario set has lower CO_2 emissions than the scenario set with subsidies on bio-SNG only but higher emissions than the scenarios with very high oil prices. In our study, the oil and gas prices assumed in the scenarios have the largest influence on the CO_2 emissions.

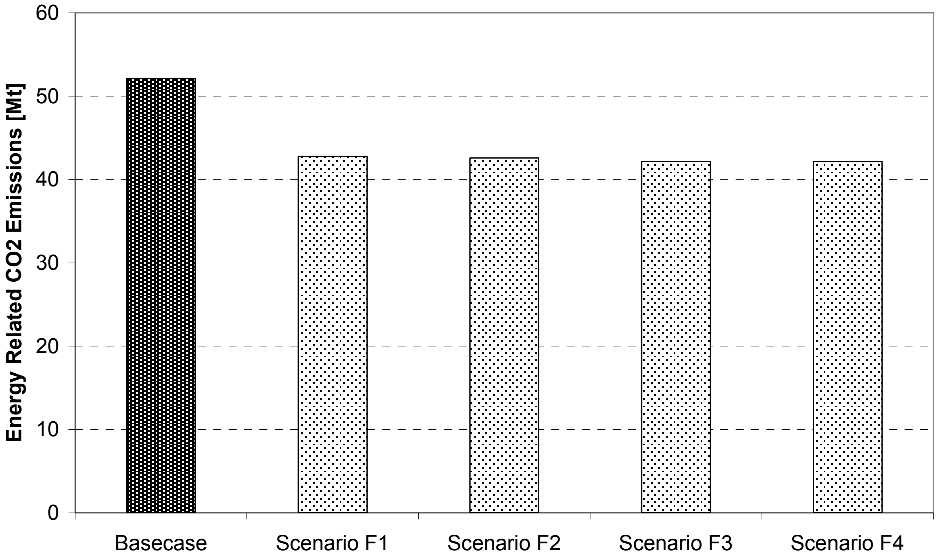

Figure 39: Energy-related CO_2 emissions in Switzerland in the Gas and Oil Price & bio-SNG Subsidies scenarios F1 to F4 for the year 2050.

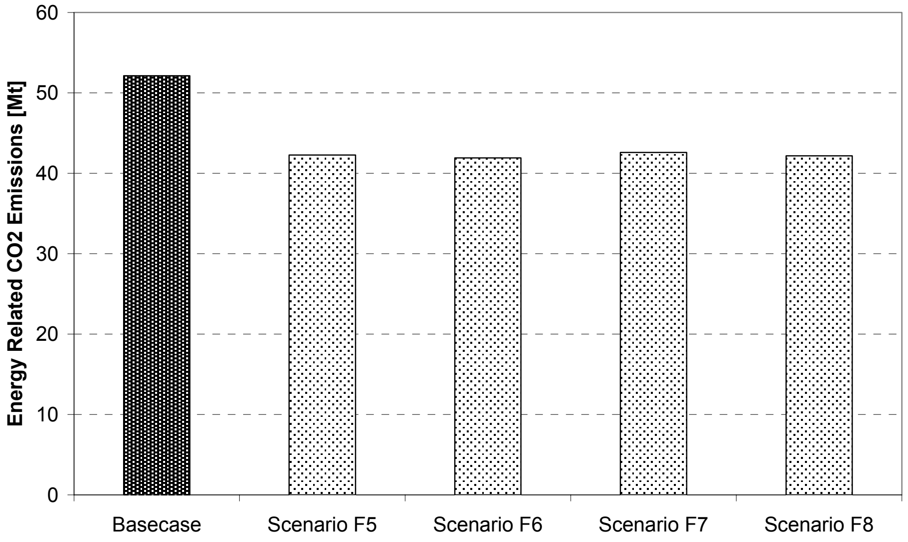

Figure 40: Energy-related CO_2 emissions in Switzerland in the Gas and Oil Price & bio-SNG Subsidies scenarios F5 to F8 for the year 2050.

In Figure 41, as an illustration, we take a closer look to the final-energy mix in the transportation sector resulting under the assumptions of the scenario F2. In this context, it is important to highlight the fuel switching away from oil products and the efficiency improvements in relation to the baseline scenario. The total final energy consumption in the transport sector is, with about 372 PJ in the year 2050, 16 % lower than in the baseline scenario. In addition, a substantial fuel switching from oil to natural gas and bio-SNG is observed. In this case, however, due to the effect of the subsidies on bio-SNG, the share of bio-SNG is somewhat larger than that of natural gas.

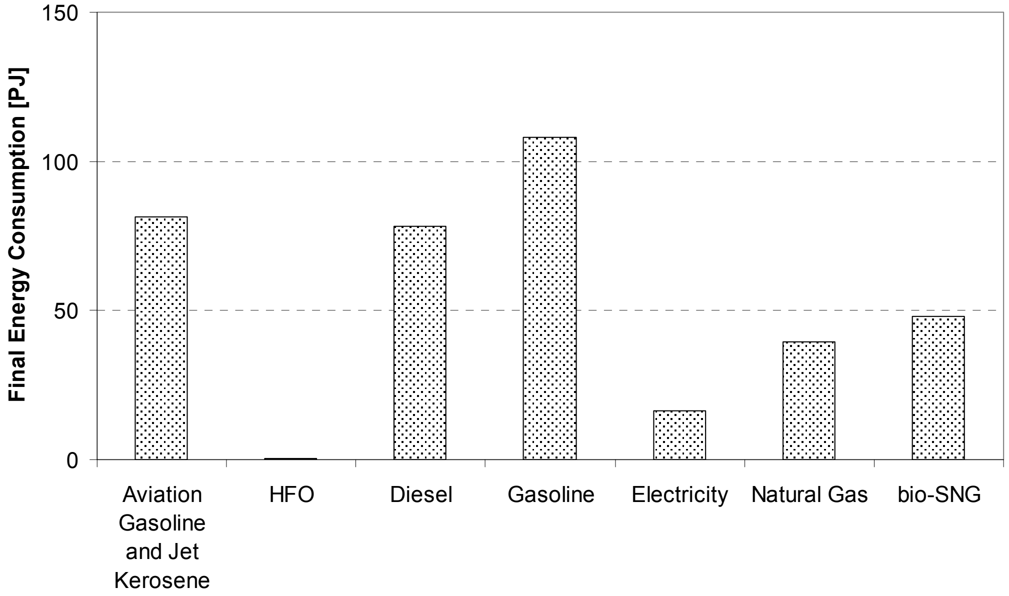

Figure 41: Total final energy consumption by fuel in the transport sector in the year 2050 for the scenario F2. In this scenario, the oil price reaches 70 US$/bbl in the year 2050 and subsidies of 5 US$/GJ (2.7 Rp/kWh) are allocated to bio-SNG from the methanation plant.

One can compare the final-energy mix in the scenario F2 with that of the scenario O3, where the oil price reached 120 US$/bbl (illustrated in Figure 20 above) but no subsidies were assigned to bio-SNG. The combination of subsidies for bio-SNG and relatively high oil prices in the scenario F2 results in a smaller total consumption of natural gas, and in a larger use of bio-SNG, in the transport sector as compared to that in the scenario O3. This results points out the fact that a combination of policy measures would be required to achieve a significant introduction of bio-SNG in the Swiss transportation sector.

Based on these results the following conclusions can be drawn:

1) The bio-SNG plant and the FT plant are competing technologies due to the similar production costs. Important in this respect is what co-product is produced and if it can be sold on the Swiss energy market. Sales of electricity are more profitable than sales of heat.
2) If investments are made in bio-SNG plants most of the produced bio-SNG is used in the transportation sector where it substitutes conventional diesel and gasoline fuelled cars.
3) If the oil price increases to about 70 to 80 US$/bbl and subsidies on bio-SNG are as high as 4 US$/GJ (2.16 Rp/kWh) to 5 US$/GJ (2.7 Rp/kWh) a significant reduction in the overall CO_2 emissions and a substantial fuel switching from oil to natural gas and bio-SNG takes place.

5. Conclusions

This report has presented an analysis of the long-term perspectives of wood-based energy technologies in the Swiss energy system using the energy-system Swiss MARKAL model. We have used several scenarios to examine the effect of a number of key variables on the introduction of wood-based energy technologies and the production of synthetic natural gas from wood (bio-SNG) in particular. The scenarios examined here encompass increases in the price of fossil fuels (oil and natural gas), introduction of subsidies for bio-SNG and selected combinations of them. In addition, we investigated the competition of bio-SNG plants with Fischer-Tropsch plants in a third set of scenarios.

This analysis sheds some light into the conditions under which wood methanation plants (bio-SNG) could play a role in the long-term evolution of the Swiss energy system. The results indicate that, under a "middle-of-the road" scenario of the evolution of the Swiss energy system and without the imposition of additional policy measures such as the CO_2 law, cost reductions in the bio-SNG plant, combined with high oil and natural gas prices and/or a subsidy to support its introduction, are required for a significant penetration of bio-SNG into the Swiss energy marketplace.

Important with respect to the use of bio-SNG is that these results favor the use of bio-SNG in the transportation sector, as opposed to the residential sector. The only significant use in the residential sector occurs if relatively small subsidies, which in this analysis subsidies could be interpreted as tax exemption for bio-SNG, are allocated on the production of bio-SNG. However, the potential is limited due to the existence of other energy saving options in the residential sector that are less costly. The transportation sector, on the other hand, offers a larger potential.

Specifically, under the assumptions outlined in this analysis, a combination of high oil prices and subsidies allocated to bio-SNG could lead to the substitution of a significant amount of conventional, petroleum-based vehicles by gas-powered vehicles and the introduction of more efficient vehicle technologies. Consequently, the combined market share of natural gas and bio-SNG in the final-energy mix of the transportation sector could increase significantly and the total final-energy consumption in this sector could be reduced. In its turn, this reduction of final-energy consumption and fuel switching towards less carbon-intensive fuels result in a significant reduction of the overall CO_2 emissions in the energy system of Switzerland.

This, of course, presupposes the successful commercialization of natural-gas vehicles in the Swiss market, which today constitute only a very small fraction of the whole car fleet (Janssen, 2005; Janssen *et al.* 2005). Still, this result illustrates how the synergetic use of bio-SNG and natural gas in the Swiss transportation sector could contribute to both reduce the dependence on oil imports, thus improving security of energy supply, and reduce the levels of CO_2 emissions, thus constituting a step towards a climate-benign energy system.

Moreover, the penetration of bio-SNG would depend, among other factors, on the competition to other wood-based energy technologies. Specifically, wood-based Fischer-Tropsch (FT) liquids could be a serious competitor to bio-SNG. Our analysis suggests that a biomass-fired facility co-producing FT liquids and electricity could be more attractive than a facility co-producing bio-SNG and heat, given that sales of electricity could be more profitable than sales of heat. In addition, the production of electricity has the advantage of a flexible site location because numerous possibilities to dispatch electricity into the grid exist. On the other hand, sales of heat are more site-specific due to a dependency on the local consumer demand. In this case, it would be ideal to build a facility co-producing bio-SNG and heat next to a potential consumer, which could be an industrial plant, commercial buildings or a large residential area having an existing heat distribution network.

However, in order to be economically and technically viable, a Fischer-Tropsch synthesis plant would necessarily have to be a large-scale facility. The logistic, environmental and public-acceptance issues that such a plant could raise make the feasibility of installing a Fischer-Tropsch synthesis plant in Switzerland appear questionable from today’s perspective. On the other hand, there is a larger flexibility regarding the size of a bio-SNG facility and smaller facilities could be built. This characteristic could make bio-SNG plants more attractive in the Swiss context. The relative advantages and disadvantages of these two technologies should be investigated further.

Co-production strategies can be useful to improve the economics of an energy carrier that is still too expensive to compete on its own in the market (Williams *et al.*, 2000; Simbeck, 2001; Yamashita and Barreto, 2004; 2005). This depends, however, on the possibility of selling the co-product at a sufficiently high price. The results of our analysis highlight the importance of exploring additional co-production strategies for bio-SNG, for instance together with electricity, and/or the feasibility of a tri-generation facility (i.e. producing bio-SNG, heat and electricity).

Continued targeted R&D activities and accumulating market experience through a demonstration and deployment (D&D) program would be key instruments to achieve the cost reductions necessary to make the bio-SNG technology competitive in the long-term. However, the bio-SNG technology would also require a combination of additional policy instruments such as targeted subsidies and, more generally, measures to enhance security of energy supply and reduce oil dependence. More importantly, synergies with the development of the natural gas industry in Switzerland and, specifically, with strategies for the introduction of gas-powered vehicles in the transportation sector must be exploited.

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Appendix 1: Calibration of the Model for the Base Year 2000

GEST	Oil	Electricity	Gas	Coal	Wood and Charcoal	District heat	Waste and industrial waste	Other renewable	Others	Total
Residential	121.0	56.6	36.3	0.1	8.6	4.6		3.4		230.6
Industry	41.5	65.1	31.9	5.6	7.0	5.6	11.4	0.4		168.5
Commerce	51.7	53.8	21.2		3.5	3.0	4.4	2.1		139.6
Transport	293.3	9.5								302.8
Non-Energy Use										
Other non-specified										
Statistical Differences including Agriculture	3.0	3.6	5.8	0.1	0.9	0.1		0.4	0.0	13.9
Total	510.4	188.5	95.2	5.9	20.0	13.3	15.7	6.3	0.0	855.3

IEA 2000	Oil	Electricity	Gas	Coal	Wood and Charcoal	District heat	Waste and industrial waste	Other renewable	Others	Total
Residential	124.3	56.6	36.3	0.5	8.9	4.6		3.5		234.6
Industry	42.5	65.1	37.5	10.1	6.8	5.6	11.3	0.3		179.3
Commerce	56.3	53.8	21.2		3.4	3.0		0.6		138.3
Transport	286.0	9.5								295.5
Non-Energy Use	18.1									18.1
Other non-specified	4.5		4.1			0.1				8.8
Agriculture	6.1	3.6			0.9			0.4		11.0
Total	537.8	188.6	99.1	10.6	20.0	13.3	11.3	4.8		885.5

MARKAL 2000	Oil	Electricity	Gas	Coal	Wood and Charcoal	District heat	Waste and industrial waste	Other renewable	Others	Total
Residential	121.5	56.8	37.9	0.4	8.5	5.1		3.5		233.8
Industry	44.8	60.8	36.9	5.3	7.4	5.3	12.3	0.1		172.9
Commerce	52.5	55.2	20.4	0.0	3.3	3.1		0.5		135.1
Transport	294.6	9.2	0.2							303.9
Non-Energy Use	16.4									16.4
Other non-specified	4.7	3.1	5.3					0.0		13.2
Agriculture	5.7	3.4			0.9			0.4		10.5
Total	540.3	188.5	100.7	5.8	20.1	13.5	12.3	4.5	0.0	885.7

Notes: The units are [PJ].

Appendix 2: Characteristics of Wood-Based Energy Technologies

Technology	Total Efficiency	Main Product Efficiency	Electrical Efficiency	Thermal Efficiency	Capacity	Investment Costs	Fixed O&M Costs	Variable O&M Costs	Plant Factor	Lifetime	Starting year	Discount Rate
	%	%	%	%	MWinput	CHF/kW input	CHF/kW input	Rp/kWh input	hours/year	years		%
Methanation	65	55	0	10	100	1583	55.4	0.198	8000	15	2010	5
Fischer-Tropsch Synthesis	55	45	10	-	400	1553	54.3	0.194	8000	15	2010	5
Decentralized CHP (Gas engine BHKW)	80	-	40	40	0.5	1500	52.5	0.375	4000	15	2005	5
Wood CHP (<2MWe) Gasification	75	-	25	50	8	2000	70	0.5	4000	15	2005	5
Wood CHP (<2MWe) Combustion	77.3	-	12	65.3	0.45	7815	273.5	1.95	4000	15	2005	5
Wood CHP (>2MWe) Gasification	86.2	-	43.3	42.9	138.5	2200	77	0.55	4000	15	2005	5
Wood CHP (>2MWe) Combustion	75.6	-	12.4	63.2	26.6	596	20.9	0.149	4000	15	2005	5
Gas heating in SFH(1)	100	-	-	100	10	1500	52.5	0.75	2000	15	2005	5
Wood chips heating (50 kWth)	80	-	-	80	0.05	1700	59.5	0.85	2000	15	2005	5
Wood chips heating (300 kWth)	80	-	-	80	0.3	750	26.25	0.375	2000	15	2005	5

Technology	Total Efficiency	Main Product Efficiency	Electrical Efficiency	Thermal Efficiency	Capacity	Investment Costs	Fixed O&M Costs	Variable O&M Costs	Plant Factor	Lifetime	Starting year	Discount Rate
	%	%	%	%	MWinput	CHF/kW input	CHF/kW input	Rp/kWh input	hours/year	years		%
Wood chips heating (1000 kWth)	80	-	-	80	1.0	500	17.5	0.25	2000	15	2005	5
Pellet heating in SFH	95	-	-	95	0.01	2500	87.5	1.25	2000	15	2005	5
Pelletizing	-	-	-	-	-	-	-	2.5	-	15	2005	5
Wood chips+Nat. Gas Combustion	-	-	45	-	75	2000	70	0.25	8000	15	2010	5
Gas distribution costs	-	-	-	-	-	-	-	0.25	-	15		5
Diesel Distribution costs	-	-	-	-	-	-	-	2.00	-	15		5

Note: The abbreviation SFH stands for single family houses.