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Replacing Fossil Fuels and Nuclear Power with Renewable Energy: Utopia or Valid Option? A Swiss Case Study of Bioenergy

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Abstract: The transition towards a reliable, sustainable, low-carbon energy system is a major challenge of the 21st century. Due to the lower energy density of many renewable energy sources, a future system is expected to be more decentralized, leading to significant changes at the regional scale. This study analyzes the feasibility of the energy transition in the Swiss canton of Aargau as an illustrative example and explores different strategies to satisfy the local demand for electricity, heat, and fuel by 2035. In particular, we assess the potential contribution of biomass. Four scenarios demonstrate what energy demand proportion could be covered by bioenergy if different priorities were given to the provision of heat, electricity, and fuel. The impact of improved conversion technologies is also considered. The results show that the sustainably available renewable energy sources in canton Aargau will probably not be sufficient to cover its forecasted energy demand in 2035, neither with present nor future biomass conversion technologies. At best, 74% of the energy demand could be met by renewables. Biomass can increase the degree of autarky by a maximum of 13%. Depending on the scenario, at least 26–43% (2500–5700 GWh) of total energy demand is lacking, particularly for mobility purposes.

Keywords: bioenergy; energy demand; energy transition; renewable energy potentials; energy system

1. Introduction

In response to the pressing need to decarbonize the world's economies and to reach CO_2 emissions targets, many countries have intensified their efforts in replacing fossil fuels with renewables, while enhancing energy efficiency and decreasing energy consumption. By adopting the Energy Strategy 2050 in 2017 [1], the Swiss population expressed its support of new approaches in the energy sector. The strategy contains measures and binding benchmarks for increasing energy efficiency and expanding the use of renewables, as well as the phasing out of nuclear power [2]. Already in 2009, several specific targets have been set for bioenergy such as the full use of available resources while maintaining sustainability and according to the principle of circular economy [3,4]. Various studies [5–8] have claimed that a self-sufficient energy supply in Switzerland is technically possible without nuclear power plants. Such an energy supply, which relies on electricity efficiency of devices and renewable energies, should not only be safer and more ecologically friendly than the previous energy system, but also more economical [9].

With the exception of hydroelectric power, the potential of renewable energies in Switzerland is still hardly utilized. In 2017, 57% of domestic electricity [10] was produced by large hydropower plants. The share of new renewable energy sources (solar, wind, biomass, and small hydropower) in electricity production in 2017 was only 6.4% [2]. The implementation of the National Energy Strategy 2050 poses a major challenge, in part because analyses, concepts, and initiatives at regional and local levels are necessary [11]. At these scales, it is necessary to take a fundamental look at all currently available and future resources and their utilization.

Without nuclear power, Switzerland's energy balance would be clearly negative. The so-called "electricity gap" could only be closed by imports. However, expanding imports would be contrary to the Swiss principles of security of energy supply. In addition, problems such as the CO_2 balance of coal-fired electricity or the storage of radioactive waste would simply be shifted abroad [12]. The Swiss population therefore voted to implement the Energy Strategy 2050.

The idea of energy self-sufficiency without nuclear power and fossil fuels will be examined in this paper by using a case study of the canton of Aargau (cf. Chapter 2.2.). Aargau is considered the "energy canton of Switzerland" because it produces almost 21% of Switzerland's electricity. Its up-to-date and comprehensible databases were examined more closely for this study [13–15]. The energy forms of heat, electricity, and fuel are considered for the time frame until 2035.

The annual cantonal electricity consumption of 4.8 terawatt-hours (TWh) is today offset by a much larger amount of electricity generation of about 12.2 TWh/year (a factor of 2.5). The additional 7.4 TWh are exported. With the implementation of the Energy Strategy 2050, nuclear power will cease to exist and should be supplemented by new renewables including biomass. It is often unclear what type and how much biomass, which can be used for a wide range of energy applications, could or should be used.

Against this background, this study examines the quantities of renewable energy that could be produced in the canton of Aargau to ensure the supply of electricity, heat, and fuel. In particular, the contribution of bioenergy will be estimated in detail. To this end, energy resources that will be sustainably available in the future are compared with cantonal demand. Scenarios are used to illustrate the proportion of renewables that could be used when heat, electricity, and fuel are prioritized differently. The influence of conversion technologies that have been developed to varying degrees is also examined.

2. Materials and Methods

2.1. Concept

In order to estimate the degree of achievable energy self-sufficiency, the total cantonal energy demand was compared with sustainable renewable energy production, both for current conditions and for future conditions until 2035. In addition to electricity, the energy forms of heat and fuel were also considered. Both on the production side and on the consumption side, final energy, i.e., the energy that reaches the consumer, was used as the baseline. The results were presented with a temporal resolution of one year, without taking seasonal fluctuations into account.

The production possibilities were determined for hydropower, wind, sun, environmental heat, and biomass renewable energy sources. In the case of biomass, a distinction was made between four woody and six non-woody biomass sources [14]. The assumptions about future consumption were based on the scenario "new energy policy, electricity generation variant renewable" from the national Energy Perspectives 2050 [16], a key document for Swiss energy policy. The energy amounts from renewable energy production (with the exception of biomass) were adopted from Ballmer et al. [13] For the sustainable production of biomass, more recent calculations by Burg et al. [14] were used.

2.2. Examination Perimeter

The canton of Aargau lies in the central part of the Swiss Midlands and has an area of 1403.81 km^2 (Figure 1). It was chosen as an example region because it is very important for the current Swiss energy supply due to its large electricity production capacities; with three nuclear power plants and several large run-of-river power stations, Aargau produces much more energy than average and is thus colloquially known as the "energy canton" in Switzerland. The region is representative of the domestic situation with regard to energy demand [17]. For these reasons, it is suitable for attracting attention and sending out signals in studies such as the present one.

Together with its comparatively good energy database records, the canton provides a suitable case for examining whether the goals of the Energy Strategy 2050 can be achieved with the available resources [13].

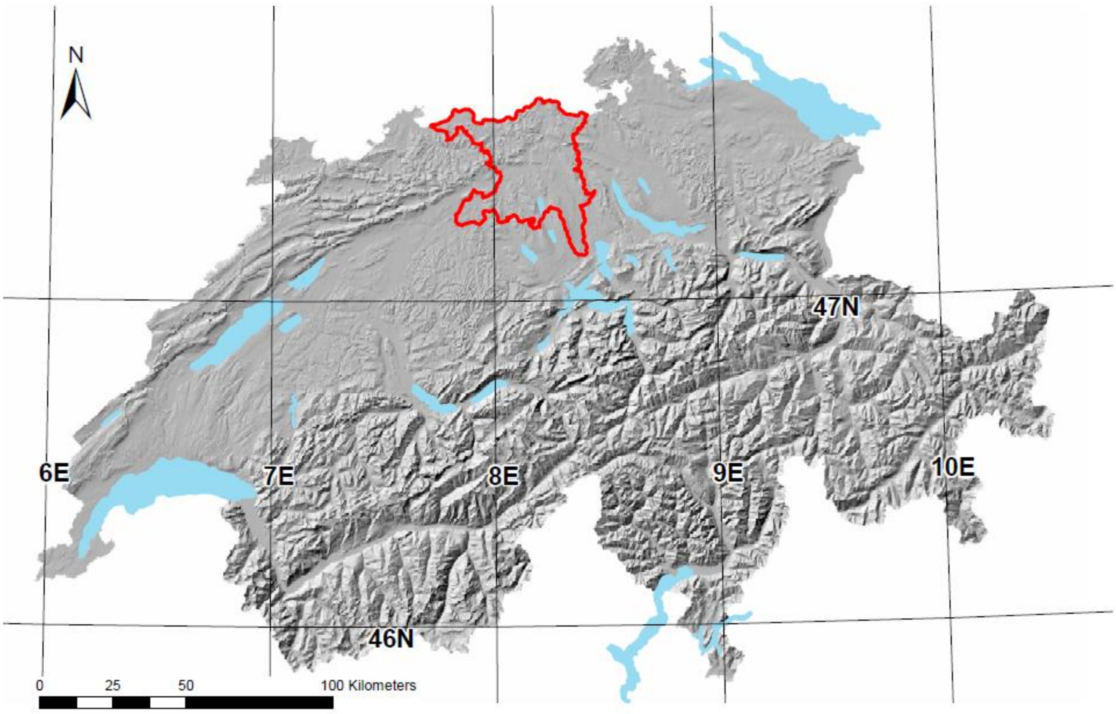

Figure 1. Location and size of canton Aargau, Switzerland.

2.3. Renewable Energy Potential

The energy potential presented here refers to the final energy provided by hydropower, wind, photovoltaic (PV) plants, and biomass [13]. In contrast to other renewables, biomass efficiency and final energy yield depend strongly on the conversion path(s) chosen. This means that burning wood directly or converting it into heat and electricity in a power plant greatly differ in terms of efficiency. Various plant categories and technologies are available for using biomass energetically to provide electricity, heat, or fuels. Thus, the additional potential of electricity generation from biomass depends, on the one hand, on the available resources, and on the other hand, on distribution to various energy facilities. Electricity generation from biomass can be tailored to demand, as bioenergy can be stored. Alternatively, biomass can also be used to provide heat or fuels. Current calculations [14,15] have been used in this study to determine the energy potential from various biomass sources. Since efficiency has not yet been considered, the presented potential corresponds to primary energy. Table 1 shows the total potential and the potential already used for electricity and heat generation from renewable energies in canton Aargau. In the case of biomass, potential is equivalent to sustainable potential, which is defined as the potential that can be derived from the theoretically available potential through ecological, economic, and socially sustainable (production and use) restrictions.

Table 1. Total potential available and the potential of electricity and heat generation from renewable energies already used in the canton of Aargau.

Energy Category	Total Annual Sustainable Potential (GWh/year)	Annual Potential Already Used (GWh/year)
Large hydropower plants > 10 MW (includes run-of-the-river, storage and weir power plants)	2812	2812
Small hydropower plants	~135	110
Wastewater power plants	0	0
Potable water power plants	~0.3	0.2
Total hydropower *	**~2947**	**2922**
Mounted or integrated photovoltaic systems	~1152	52
Open space photovoltaic systems	0	0
Total photovoltaic power	**~1152**	**52**
Large wind turbines	~ 50	0
Small wind turbines	0.02	0.02
Total wind power	**~50**	**~0.02**
Total deep geothermal power	**~0**	**0**
Total solar thermal power	**~228**	**38**
Total environmental heat	**399**	**399**
Forest wood **	584	247
Waste wood **	150	94
Industrial wood residues **	131	153
Wood from landscape maintenance **	94	53
Sewage sludge **	106	89
Manure **	328	31
Agricultural crop by-products **	72	1
Organic household waste **	81	124
Green waste **	131	51
Industrial bio-waste **	58	43
Total biomass power	**1735**	**886**

Note: * Only canton Aargau's share (7%) of Swiss hydropower production from 2003 to 2012. ** Primary energy, not considering efficiency.

2.3.1. Electricity from Hydropower

In canton Aargau, three major Swiss rivers—the Aare, Limmat, and Reuss—flow into the Rhine. Consequently, the use of run-of-river power plays a major role. Information on existing large and small hydropower plants on natural waters used in this study comes from the Statistical Yearbook "Aargauer Zahlen" [18]. The average Swiss hydropower production from 2003 to 2012 was recalculated to include only canton Aargau's share (7%). The data on the current additional potential comes from the Energy Department of the canton of Aargau [19]. The data on wastewater and drinking water power plants comes from estimates by Ballmer et al. [13]. The data on the additional potential is taken from the PANEIKA study (Potential analysis of new energies for electricity production in the canton of Aargau) [20].

2.3.2. Electricity from Solar Energy

Although the potential is great, solar power currently plays a subordinate role in the canton of Aargau and throughout Switzerland. Suitable areas (especially roofs and facades) could still be developed [21], especially as new and efficient technologies (e.g., thin-film cells, dye solar cells) are now affordable. A disadvantage of solar energy is the large seasonal and daily fluctuations in production. Even if production partly follows the fluctuations in demand, the need for storage and compensation for such volatile energy sources is likely to increase. The information on existing photovoltaic systems comes from the Aargau Task and Budget Plan 2015–2018 [22], based on Swissgrid's register of guarantees of origin and compared with Swisssolar's data [23]. The potentials (Table 2) were derived from the cantonal solar register [24,25], considering economic and political restrictions (for example, removing the potential of roofs under protection of local heritage building codes) as well as the competitive use of roofs for solar thermal energy (which subtracts 4.5% of usable areas). In the case of technically usable roof areas, an additional reduction was made due to the high stability requirements (this subtracted 50% of the roof areas in addition to the 50% reduction for flat roofs and 25% reduction for pitched roofs already in the solar register [24]). The stability requirements are often not met for roofs on farms [26]. This additional reduction halves the total potential in canton Aargau from around 2300 GWh per year to around 1150 GWh per year. However, it remains to be seen how this will develop in the future.

Table 2. What contribution should bioenergy make in 2035? An estimate derived from the difference between renewable energy production and the demand for heat, electricity, and mobility.

Energy form Based on Renewable Sources	Production in 2035 (GWh)	Usage with Increased Efficiency by 2035 (GWh)	Energy Gap to be Covered by Bioenergy or Other Means (GWh)
Total heat	**627**	**3097**	**2470**
Solar thermal	228		
Geothermal	0		
Ambient heat	399		
Total electricity	**4149**	**4219**	**70**
From PV	1152		
From water	2947		
From wind	50		
Total fuel	**0**	**2628–6188**	**2628–6188**
as SNG	0	4560	4560
as liquid fuel	0	3645	3645
as electricity	0	1000	1000
Aviation fuels	**0**	**1628**	**1628**

2.3.3. Electricity from Wind Energy

In the canton of Aargau, little electricity is currently produced from wind (see Table 1). In 2015, 34 large Swiss wind turbines produced around 100 GWh of wind power [27]. The aim is to produce around 600 GWh/year of wind power by 2020 and as much as 4000 GWh/year by 2050. Large wind plants have not yet been installed, and small plants have comparatively low capacity due to low wind speeds. The additional potential that can be realized is currently regarded as limited, primarily due to ecological and political restrictions (including problems of social acceptance of wind turbines). The information on existing wind turbines is taken from the Task and Financial Plan 2015 to 2018 [27] and Swissgrid's Guarantee of Origin List. The information on the additional potential of large wind turbines is based on the knowledge of AEW Energy AG and includes the Aargau share of currently planned wind farm projects [26]. Due to acceptance problems, only a few locations are considered for future wind farms [28].

2.3.4. Electricity from Deep Geothermal Energy

No deep geothermal plant operations exist in Switzerland. Although the technology of hydrothermal plants is well developed, its implementation depends on deep natural aquifers. Less site-dependent petrothermal plants are less developed. The construction of such plants is therefore associated with higher risks [29,30]. The information on the status of deep geothermal plants (hydro- and petrothermal plants) provided by Ballmer et al. [13] is still valid today. The additional potential was set to zero due to a lack of concrete projects as well as great uncertainties in implementation.

2.3.5. Heat from Solar Energy (Solar Thermal Energy)

Around 85,000 solar thermal systems are in operation in Switzerland [31]. The current number of systems in the canton of Aargau is not recorded, but the cantonal subsidy database allows for rough estimates. Nathani et al. [32] estimated the capacity for 2010 at around 63 MW and the annual amount of heat generated from solar thermal systems at around 38 GWh/year. The potential for solar heat was derived based on data from the cantonal solar register (Table 2): 4.5% of the economically usable roof areas is reserved for heat generation, i.e., around 57 GWh/year of electricity cannot be generated in this area (own calculation based on METEOTEST [33] and [25]). Based on Swissolar [34,35], we calculated the heat yield per area to be four times higher than electricity, which leads to a heat quantity of about 230 GWh/year.

2.3.6. Environmental Heat

Canton Aargau uses a total of around 400 GWh/year of environmental heat [36], primarily with geothermal probes (approximately 91% of the systems) but also with heat pumps that use heat from groundwater, surface water, spring water, or wastewater and from the air. The figures for heat production capacity refer to the year 2010 [32]. For geothermal probes and heat pumps, which extract heat from groundwater or surface waters, it is difficult to quantify the additional potential of the usable amount of heat. The AGIS Geothermal Probes Public Map dataset only provides information on where which type of heat utilization is possible in the canton [37]. Only the potential already used (399 GWh) is taken into account.

2.3.7. Energy Potential from Biomass

The various biomass types available for energy generation were differentiated to calculate biomass potentials [14,15]. Depending on the type, different forms of energy (electricity, heat, and fuel) can be produced. As far as electricity is concerned, biomass is currently the second-largest energy source in Switzerland after hydroelectric power. Most of this is due to the content of organic material in the waste material burned in incineration plants. Biomass currently accounts for 2.5% of total electricity production [38].

In canton Aargau, the electricity generated from biomass comes primarily from waste incineration plants, followed by biogas plants that are connected to cogeneration plants that convert biogas into electricity directly on-site. Only about half of the energy from waste incineration plants counts as renewable energy, based on the proportion of biomass in the waste. At 78 GWh/year, electricity production from biomass in canton Aargau, similar to the rest of Switzerland, is currently low.

The biomass potentials are indicated as primary energy (Figure 2), i.e., as the available energy contained in the resource. The efficiencies of the conversion technologies are not considered. Consequently, the quantities of energy indicated are only partially available as final energy.

For all 10 biomass categories, the "theoretical," "sustainable," "already used," and "additional potential" were determined for the current conditions. The theoretical potential includes the maximum domestically produced biomass that could be used. The sustainable potential can be derived after deducting ecological and economic as well as legal and political restrictions. Figure 2 shows only the theoretical and the sustainable potential. The potential "already used" corresponds to the biomass that has already used for energy purposes (see [14,15]).

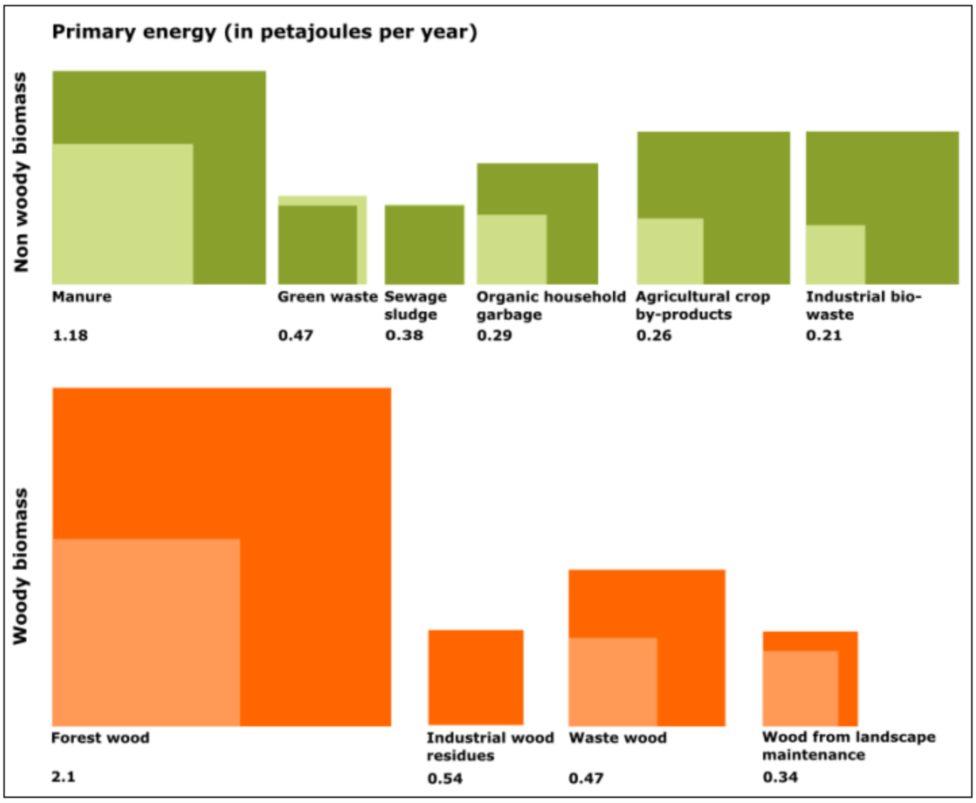

Figure 2. Theoretical (darker) and sustainable (lighter) biomass potential of canton Aargau differentiated by biomass type.

2.4. Energy Consumption Today and in the Future: Outlook for 2035

Current and future energy consumption is based on the statistics listed below and on the estimated savings potential of the Swiss federal government [22].

2.4.1. Electricity

Annual electricity consumption in 2016 amounted to 4849 GWh in the canton of Aargau. In 2035, it is assumed that there will be an increase in electricity demand mainly due to electromobility, but a decrease in demand due to an increase in efficiency. Based on current electricity consumption, there is enormous potential for economic savings. According to the federal government's targets [22], electricity consumption in Switzerland must be reduced by 13% by 2035, i.e., an increase in efficiency in the electricity sector of 13% is expected. LED technology reduces consumption for lighting, high-efficiency pumps for water, speed-controlled motors for driving, and the highest efficiency classes (A+++) for appliances. Control technologies (that limit use to when it is required, e.g., via motion sensors, sleep mode) and the adaptation of industrial processes can further reduce consumption significantly. If the federal government were to increase efficiency by 13%, only around 4219 GWh of electricity would be required in the canton of Aargau in the future.

2.4.2. Heat

The cantonal energy statistics for 2016 do not differentiate whether the demand for natural gas and crude oil is for heat supply or other uses. Although fuels and natural gas are listed separately, the intended use is not apparent. In households, commerce, trade, services, and industry, the majority of gas and oil consumption is likely to be used for space heating and hot water. For 2016, fuel consumption of 9879 TJ (2744 GWh) and natural gas consumption of 9680 TJ (2689 GWh), i.e., a total consumption of 5433 GWh/year, are reported [39,40].

In the European Union, buildings account for 40% of total final energy consumption. The greatest savings potential lies in space heating and hot water, which account for 85% of building energy consumption. These areas also hold great substitution potential for gas and oil through renewables. Residential buildings (detached and multi-family houses) could also be supplied with 100% solar thermal energy [41]. In rural areas, oil-fired heating systems and inefficient wood stoves should generally be replaced, e.g., by wood pellet heating systems when heating systems are renewed. Solar thermal energy is to be used for hot water in summer [42].

Inspired by the federal government's targets, energy consumption for heating in Switzerland should be reduced by 43% by 2035 [22]. This would lead to a reduction of the current heating requirement from 5433 GWh/year to 3097 GWh by 2035.

2.4.3. Fuel

With a total consumption of 5036 GWh (18,131 TJ) [8] of fossil fuels in 2016, road and rail transport in canton Aargau devours considerable amounts of energy that can hardly be covered by biofuels [8]. The use of biomass for these biofuels is restricted by the principle that food production always has priority over energy use (see Federal Biomass Strategy [3]). The Swiss Federal Office of Energy, therefore, gives priority to the economical and rational use of energy (position paper for the future 2035 SFOE [39]). There must be no direct or indirect displacement effects, nationally or abroad [43]. Should biofuels become established, it is still unclear from which resources they should be produced and whether they should be produced in Switzerland or imported from abroad. Although the import of sustainably produced biomass is possible, it is controversial in the public debate.

Biofuels are only one alternative to fossil fuels. From today's perspective, three technologies are conceivable to replace or reduce the use of internal combustion engines: (i) battery-powered electric vehicles, (ii) hydrogen-powered vehicles that convert hydrogen into electricity using fuel cells, and (iii) various hybrid systems. Battery-based engines with rather short ranges will be preferred in urban traffic, while hydrogen-based vehicles are more suitable for long distances. All technologies are much more efficient than a combustion engine, which converts less than 25% of the fuel's energy content into kinetic energy. Electric motors, on the other hand, have an efficiency of over 90%. It is difficult to predict which technologies will prevail. Yet, assuming a constant motorization rate and mileage, the future primary energy demand to be covered by renewable energies will be significantly lower.

Future fuel consumption can be estimated as follows: assuming an average future electricity consumption for electric vehicles of 15 kWh/100 km [44], the annual electricity requirement for an annual driving distance of 12,000 km would be 705 GWh/year for a total of 391,582 passenger cars [45] in the canton of Aargau. For heavy transport vehicles, it is difficult to find reference data. For comparison, a transport vehicle was converted from diesel to electric and undertook a test route: a 50 km trip to the Gotthard Pass and back with an altitude difference of over 1600 m. The vehicle consumed 100 kWh/100 km. Taking this figure as a reference, 6175 electric trucks in Switzerland would require approximately 247 GWh/year to drive the average distance of 40,000 km/year each [45].

Without air traffic, the total electricity requirement for mobility amounts to nearly 1000 GWh/year (705 + 247 GWh/year) and can be met by synthetic natural gas (SNG), liquid fuel, or electricity. For comparison, the unit passenger kilometers (pkm) can be used as a reference unit for conversion into other forms of energy. This unit describes the energy in terms of distance traveled by a passenger car. Accordingly, the total 1000 GWh of electrical energy required for mobility corresponds to 9.44×10^9 pkm. To provide 9.44×10^9 pkm with SNG the energy requirement amounts to 4560 GWh; with liquid fuel to 3645 GWh, due to the higher conversion efficiency [46].

According to Swiss total energy statistics in 2016 [47], the demand for aviation fuels for long-haul mobility in Switzerland and 2016 amounted to 74,170 TJ. Assuming that the consumption of aviation fuel is proportional to the population, the demand corresponds to 5859 TJ or 1628 GWh (7.9%) for the canton of Aargau.

2.5. Balance of Production and Consumption

The following overview shows an estimate of whether renewable energy production in the canton of Aargau will be able to meet future demand or how close the forecast production will come to the targets. Table 2 compares the renewable energy quantities that can be produced sustainably with the demand for heat, electricity, biogas/syngas, and fuel in 2035. An increase in efficiency is assumed according to the Energy Strategy Aargau 2015.

Biomass should therefore contribute just under 2500 GWh of heat. The electricity demand is covered by other renewables and does not have to be supplemented with electricity from biomass. Mobility, however, requires around 1000 GWh of electricity, 4560 GWh of SNG, or 3645 GWh of liquid biofuel. A further 1628 GWh of liquid fuel would be added to cover the cantonal aviation fuel requirements.

2.6. Biomass Conversion Paths

As the pressure on biomass as an energy source could massively increase in the future, it is worth considering how and for what purpose biomass should be used and converted. Biomass is unique among renewable energy sources because it can be converted and used in many different ways. Today, the conversion processes are limited to a few paths and technologies. In the future, however, further and potentially more efficient processes will be added (Table 3).

This study distinguishes between current and future technologies to show how much final energy could be generated with different technology portfolios in 2035. The calculations are limited to the most energy-efficient conversion paths for the respective biomass types.

Table 3 shows the considered conversion paths with the corresponding conversion efficiencies. The conversion efficiencies refer to the biomass input in energy units. A negative efficiency therefore describes the percentage consumption related to the biomass input in the corresponding energy form.

Table 3. Overview of the efficiencies of the considered conversion paths in relation to the biomass input. (Conversion efficiencies of anaerobic digestion and hydrothermal gasification vary depending on the type of biomass used. These are more precisely broken down in Figure 3.).

Conversion Process Chains	Future Technology	Conversion Efficiency (%)			
		Heat	Electricity	SNG	Liquid Fuel
Woody Biomass					
Solid fuel combustion—decentralized *(SCCER BIOSWEET—Biomass Technologies Database 2015 [48])*	–	89	−0.02	–	–
Solid fuel combustion—Organic Rankine cycle [48,49]		66	13	–	–
Solid Fuel Combustion—Water-steam cycle *(SCCER BIOSWEET, Biomass Technologies Database 2015 [48])*		35	18	–	–
Solid Fuel Combustion—Water-steam cycle—Flue gas treatment (Waste incineration plant) [48]		26	19	–	–
Gasification—Methanation [46]	x	9	3	74	–
Gasification—Methanation—Solid oxide fuel Cell [50]	x	17	45	–	–
Gasification and Electrolysis—Methanation [50]	x	–	−145	170	
Solvent-based biomass deconstruction [51]	x	–	1.1	–	41
Non-Woody Biomass					
Anaerobic digestion—CO_2 separation [52]		–	–	13–78	–
Anaerobic digestion—Internal combustion engine (SCCER BIOSWEET—Biomass technologies database 2015 [48,53])		2–13	4–24	–	–
Hydrothermal gasification [50,54]	x	–	5	46–68	–
Hydrothermal gasification—Solid oxide fuel cell [50,54]	x	12–17	33–46	–	–
Hydrothermal liquefaction [55]	x	–	–	–	35
Others					
Gas heating [56]		98	–	−100	–
Heat pump [50]		400	−100	–	–

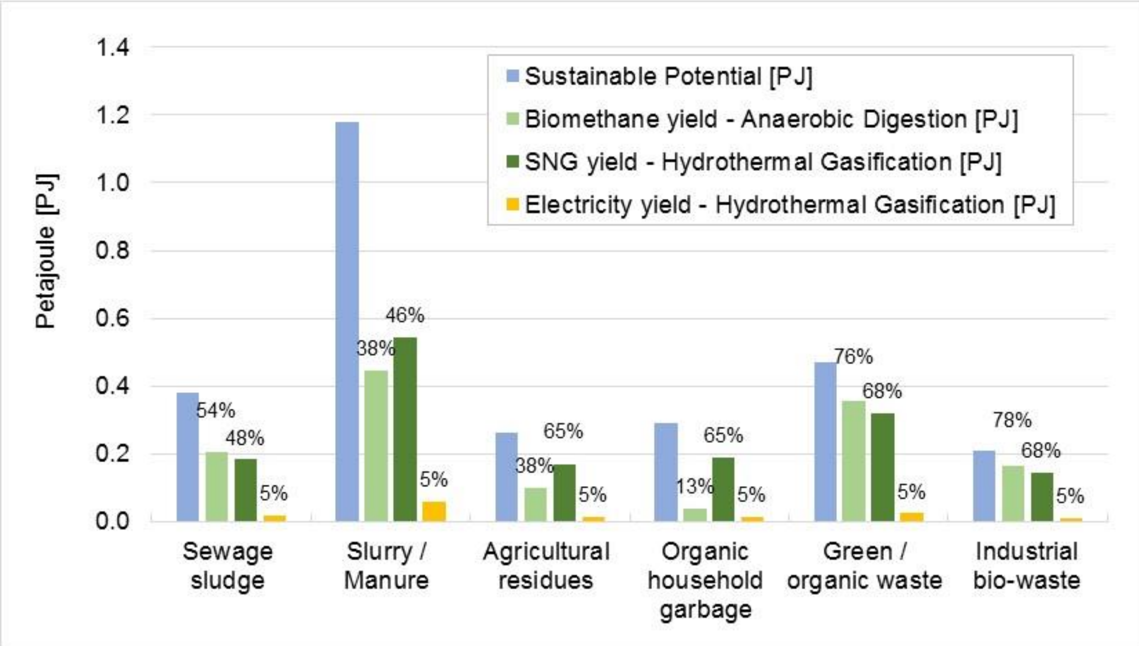

Figure 3. Conversion efficiency of anaerobic digestion and hydrothermal gasification of various non-woody biomasses.

Particular attention was paid to the suitability of a given biomass for the corresponding conversion path. The majority of the technologies available in the future will displace or replace current technologies. Nevertheless, different biomass types will probably only be converted by a certain technology. Due to technological and other limitations, the following boundary conditions have been defined:

- All types of wood from landscape maintenance and waste wood are not used in decentralized small-scale furnaces.
- Due to problematic components (e.g., sulfur), which act as catalyst poison in very low concentrations (in the range of parts per billion), wood from landscape maintenance and waste wood is not fed into the conversion path "Gasification—Methanation" and "Gasification—Methanation—Solid oxide fuel cells."
- Contaminated waste wood is burned in waste incineration plants.
- Uncontaminated waste wood is fed into the "Solid combustion—Organic Rankine cycle (ORC)" or "Solid combustion—Steam process," since flue gas cleaning can be designed more reliably and economically for this type of biomass than for contaminated waste wood.
- Wherever possible, all sustainably available biomass should be used.

For the convertible woody biomass types, uniform efficiencies were used for the conversion paths. In anaerobic digestion and hydrothermal gasification, the potential biomethane yields were differentiated according to the different biomass types (Figure 3). In relative terms, the biomethane yields for anaerobic digestion amount to 13–78% of the sustainable biomass potential, depending on the biomass type [52]. In hydrothermal gasification, the efficiency of the conversion varies between 46–68% depending on the biomass type and its inorganic fraction, with a constant electricity yield of 5% [54]. Theoretically, higher SNG yields could be achieved at the cost of electricity yields.

For hydrothermal liquefaction, no conversion efficiencies could be differentiated according to the biomass type. Based on the data provided by Kaltschmitt et al. [55], a uniform conversion efficiency of 35% was calculated as the mean value from the described processes.

This study makes clear which conversion paths best fulfill the objectives of different scenarios. Dynamic influences, such as full load hours or associated performance-related investment costs, are not considered. In the same vein, the allocation of different types of biomass to possible conversion paths is only marginally discussed.

2.7. Scenarios

Table 4 shows the important characteristics and distinguishing features of four scenarios: "without biomass," "heat," "electricity," and "storage". None of the scenarios claim that future energy supply and consumption could actually develop in this way. Rather, as extreme scenarios, they make clear the different development paths and the corresponding consequences for bioenergy use.

Table 4. Calculated variants (heat pump, current and future technologies, and biomass energy products for mobility) for the scenarios 0a until 8b.

Scenario	Nr.	Heat Pump	Current Technologies (For Biomass)	Future Technologies (For Biomass)	Electricity (For Mobility)	SNG (For Mobility)	Liquid Fuel (For Mobility)
Without biomass	0a				X		
	0b	X			X		
Heat	1a		X		X		
	1b	X	X		X		
	2a			X	X		
	2b	X		X	X		
	3b	X		X		X	
	4b	X		X			X
Mobility	5b	X		X	X		
	6b	X		X		X	
	7b	X		X			X
Storage	8b	X		X		X	

The scenario "without biomass" shows the degree of self-sufficiency that renewable energies could achieve if biomass use for energy purposes were completely excluded (Table 4, 0a and 0b). This makes it possible to answer the question of whether bioenergy is relevant or negligible for achieving the 2050 energy targets.

The primary aim of the "heat" scenario is to cover the heat demand as efficiently as possible by using "Current Technologies" (1a and 1b) and "Future Technologies" (2a–4b) for biomass conversion. Within this scenario, the influence of using or dispensing heat pumps is also examined (Figure 4). Assuming that by 2035 most consumers will be equipped with heat pumps that convert ambient heat (air, water, subsurface) into usable heat, the production of heat will be significantly more efficient. A coefficient of performance (COP) of four was used for the efficiency of the heat pump [30]. Once the heat requirement is met, the remaining biomass will first be used to cover the general electricity requirement, then to meet the electricity requirement that includes road transport (2b), and finally to meet the energy requirement covered by SNG (3b) or liquid fuel for mobility (4b).

In the "mobility" scenario (5b to 7b), as much fuel as possible is produced from biomass because heat and electricity can also be generated in other ways. The aim is to show how much energy could be provided in the form of fuels while investigating the influence that possible forms of SNG energy, liquid fuel, or electricity have on covering mobility requirements (Table 4).

In the last scenario, "storage" (8b), as much energy as possible should be stored seasonally as SNG. The seasonal imbalance in electricity production, especially the winter demand, could thus be partially compensated. The study calculates the maximum amount of bioenergy that could be transferred into the winter months and the impact of the use of this technology on the overall coverage (Table 4).

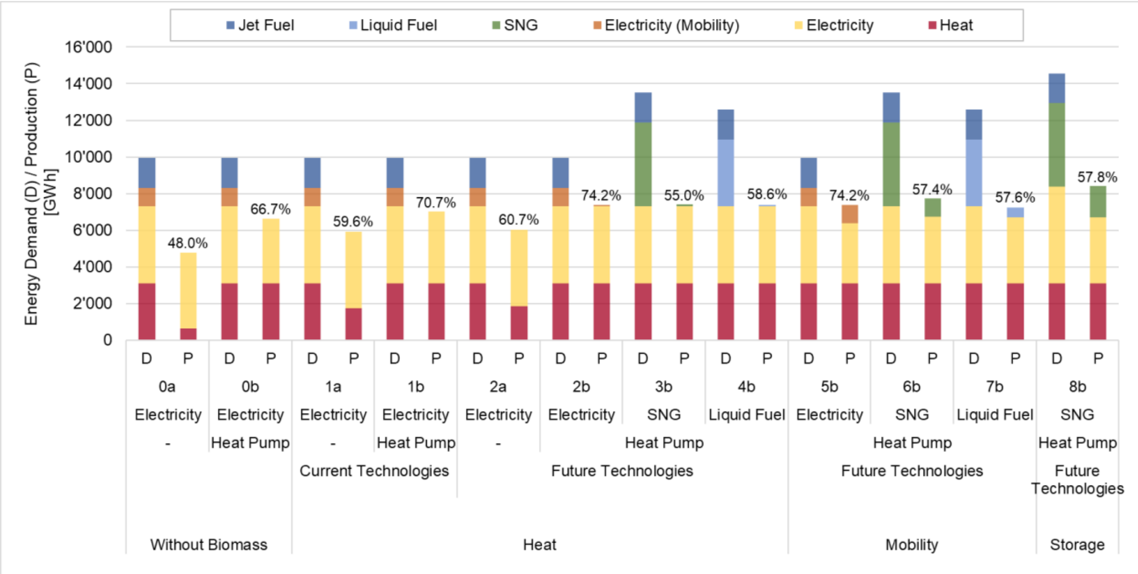

Figure 4. Overview of the scenarios 0a–8b, separated into energy demand (D) and production (P) for various forms of energy, with a percentage of the total coverage of each scenario.

3. Results

Figure 4 and Table 5 summarize the results of the four scenarios. Table 5 contains the exact values and also lists the degrees of self-sufficiency of the individual forms of energy. The percentages in Figure 4 and Table 5 describe the degree of self-sufficiency as the sum of the renewable energy produced in relation to the total demand. Table 5 shows that the demand for heat and largely also for electricity (excluding electric mobility) is covered in all heat scenarios with heat pumps (0b, 1b, 2b, 3b, 4b). In scenarios 0a–2b, the demand for electric mobility is covered exclusively by electricity as far as possible. This is justified by the fact that, based on the findings from scenarios 5b–7b, mobility can be provided most efficiently by electricity. For the remaining scenarios, the fuel requirements for road transport are shown for the relevant forms of energy. This results in different total requirements in the GWh units.

The scenario "without biomass" (0a, 0b) makes it clear that bioenergy is a component in the future energy system that should not be underestimated, since energy production is expected to remain well below the total energy demand. Without the provision of bioenergy, it will not be possible to even remotely cover the energy demand in the canton of Aargau. The calculations also make it clear what influence the widespread use of heat pumps has on meeting demand (+18.7%, difference 0b–0a), as well as on the demand for environmental heat, which could greatly increase the pressure on groundwater and water bodies.

If the energy recovery from biomass is added but the use of heat pumps is abandoned in the "heat" scenario (1a, 2a), the coverage of energy demand could be increased by 11.6% (difference 1a–0a, using current technologies) and 12.7% (difference 2a–0a, using future technologies) compared with the "without biomass" scenario.

If heat pumps are used in addition to biomass (1b, 2b), the degree of self-sufficiency could be increased by 4.0% with current technologies and by 7.5% with future technologies compared with the scenario "without biomass" (0b). It should be emphasized that scenario 2b as well as scenario 5b (see Figure 4 and Table 5) achieved the highest degree of self-sufficiency of all scenarios with 74.2%.

Table 5. Energy demand, production, and degree of self-sufficiency (autarky) of total energy demand for various forms of energy (scenarios without heat pumps 0a until 2a, with heat pumps 0b until 8b).

Scenario			Sum	Heat	Electricity	Electricity (Mobility)	SNG	Liquid Fuel	Jet Fuel
Without biomass	0a	Demand [GWh]	9944	3097	4219	1000			1628
		Production [GWh]	4776	627	4149	0			0
		Autarky [-]	48.0%	20.2%	98.3%	0.0%			0.0%
	0b	Demand [GWh]	9944	3097	4219	1000			1628
		Production [GWh]	6629	3097	3532	0			0
		Autarky [-]	66.7%	100.0%	83.7%	0.0%			0.0%
Heat with current technology	1a	Demand [GWh]	9944	3097	4219	1000			1628
		Production [GWh]	5923	1751	4172	0			0
		Autarky [-]	59.6%	56.5%	98.9%	0.0%			0.0%
	1b	Demand [GWh]	9944	3097	4219	1000			1628
		Production [GWh]	7035	3097	3938	0			0
		Autarky [-]	70.7%	100.0%	93.9%	0.0%			0.0%
Heat with future technology	2a	Demand [GWh]	9944	3097	4219	1000			1628
		Production [GWh]	6034	1838	4196	0			0
		Autarky [-]	60.7%	59.3%	99.5%	0.0%			0.0%
	2b	Demand [GWh]	9944	3097	4219	1000			1628
		Production [GWh]	7379	3097	4219	63			0
		Autarky [-]	74.2%	100.0%	100.0%	6.3%			0.0%
	3b	Demand [GWh]	13,504	3097	4219		4560		1628
		Production [GWh]	7421	3097	4219		105		0
		Autarky [-]	55.5%	100.0%	100.0%		2.3%		0.0%
	4b	Demand [GWh]	12,589	3097	4219			3645	1628
		Production [GWh]	7377	3097	4219			62	0
		Autarky [-]	58.6%	100.0%	100.0%			1.7%	0.0%
Mobility with future technology	5b	Demand [GWh]	9944	3097	4219	1000			1628
		Production [GWh]	7379	3097	3282	1000			0
		Autarky [-]	74.2%	100.0%	77.8%	100.0%			0.0%
	6b	Demand [GWh]	13,504	3097	4219		4560		1628
		Production [GWh]	7749	3097	3657		995		0
		Autarky [-]	57.4%	100.0%	86.7%		21.8%		0.0%
	7b	Demand [GWh]	12,589	3097	4219			3645	1628
		Production [GWh]	7256	3097	3603			556	0
		Autarky [-]	57.6%	100.0%	85.4%			15.3%	0.0%
Storage with future technology	8b	Demand [GWh]	14,565	3097	5280		4560		1628
		Production [GWh]	8415	3097	3618		1700		0
		Autarky [-]	57.8%	100.0%	68.5%		37.3%		0.0%

Figure 5 compares the demand for mobility purposes in passenger-kilometers (pkm) of production (of 2b, 3b, 4b) that can be made available for mobility in the form of electricity, SNG or liquid fuel after covering heat and electricity demands (excluding electromobility). The highest degree of self-sufficiency was calculated for electromobility at 6.3% (scenario 2b). SNG covers just 2.3% (scenario 3b) and liquid fuel 1.7% of demand (scenario 4b). This makes clear that the energy requirements for road, rail, and air transport cannot be met in any form.

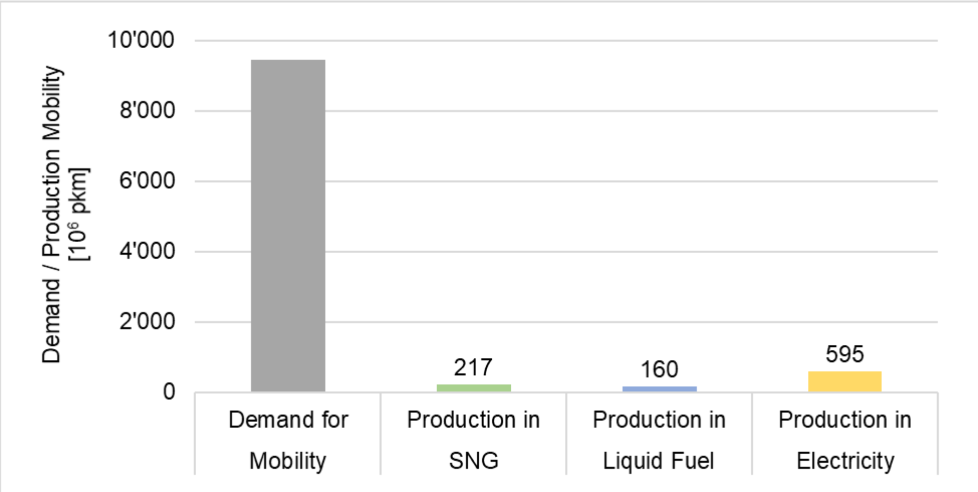

Figure 5. Energy demand and production for mobility differentiated by energy sources for the scenarios 2b (electric mobility), 3b (mobility with SNG), and 4b (mobility with liquid fuels), assuming that bioenergy is first used to cover electricity and heat demands and only thereafter to serve mobility purposes.

The influence of the different forms of energy (electricity, SNG, liquid fuel) on mobility only becomes clear in the overall context. The coverage of the three scenarios with heat pumps (2b, 3b, 4b) varies from 55–74.2%. For SNG-based mobility (3b), 45.0% of the energy requirement could not be covered. For the electric mobility scenario (2b), this share is only 25.8%. However, the value of the overall degree of self-sufficiency is partly misleading. Table 5 (3b and 4b) shows that the coverage of mobility requirements for SNG (total self-sufficiency 55.0%) is higher at 2.3% than for liquid fuel (total self-sufficiency 58.6%) at 1.7%.

In all three mobility scenarios "electricity" (5b), "SNG" (6b), and "liquid fuel" (7b) as much bioenergy as possible should be used for mobility purposes. Electricity could cover 100% of mobility needs, SNG only 21.8%, and liquid fuel only 15.3% (without jet fuel). If bioenergy is made available for mobility, it will, of course, be lacking elsewhere. Nevertheless, in scenario 5b, with 100% coverage of mobility requirements, coverage of total electricity of 82.0% (4282 GWh/5219 GWh) is achieved. Thus, only 18% (937 GWh) of electricity is missing (Table 5). The high conversion efficiency of electricity in pkm [46] is decisive for the positive result. In scenario 6b, 86.7% of the electricity demand could be covered by 21.8% of the mobility demand. In scenario 7b, 85.4% could be covered by 15.3% of the mobility demand (Table 5). The mobility scenarios (5b, 6b, and 7b) could also be reproduced without the use of heat pumps. In the overall context, however, higher self-sufficiency can be achieved through the use of heat pumps.

Comparing scenarios 3b (mobility with SNG, priority heat) and 6b (mobility with SNG, priority mobility) shows that the degree of self-sufficiency is higher when SNG is used for mobility (6b) than when SNG provides electricity and heat (3b). This is not surprising, as the conversion losses from SNG to electricity and heat are eliminated in these process chains (shown in Table 3). This correlation is even more pronounced when using current technologies with lower electrical efficiencies. Particularly with the technologies available today, the production of heat and electricity from SNG should be avoided as long as there is a demand for SNG.

A similar correlation can be seen in the "energy storage" scenario (8b). Compared with all other scenarios, the degree of self-sufficiency in electricity is lowest at 68.5% (Table 5 due to the additional electricity requirement for electrolysis. Nevertheless, the scenario achieves a comparatively high degree of self-sufficiency at 57.8% because the conversion losses from chemical to electrical and thermal energy could be saved in these process chains (shown in Table 3).

Overall, it is clear that the use of future technologies in combination with heat pumps could at best cover heat and electricity needs and provide a small share of mobility needs. At 74.2%, the highest degree of self-sufficiency is achieved with electricity-based mobility (5b). It is important to note that in no single scenario could the sustainably available biomass potential be used to produce additional jet fuel.

4. Discussion

The analysis shows, by way of example, whether and to what extent a region such as the canton of Aargau can supply itself with renewable energy in the future and what role the use of biomass plays. The results show that in the heat scenarios with heat pumps 2b, 3b, and 4b (see Table 4), heat and electricity can be covered 100%. Overall, however, the canton will not be able to independently supply itself with renewable energies by 2035, neither with current nor with future technologies. It is also clear that different scenarios, i.e., the choice of different energy sources (such as biomass and solar energy) and preferred consumption categories (mobility and heat), are decisive for obtaining the maximum possible degree of self-sufficiency. Whichever option the canton chooses, the supply of renewables is only sufficient to cover a maximum of 74% of the total annual energy requirement. The anticipated development of biomass conversion technologies is not likely to significantly change this.

Our calculations also clarify the potential contribution of biomass and its optimal use within the energy system. Although bioenergy has numerous advantages [57], it contributes little to the implementation of the Energy Strategy 2050 in the long term for this case study when it comes to replacing large amounts of nuclear power with bioenergy. Nevertheless, bioenergy can contribute to the transformation. Additionally, excess electricity could increase the biomethane yield of the remaining sustainable biomass potential with hydrogen from electrolysis. Large CO_2 sources, for example from industrial combustion and calcination processes, are required for the production of further SNG by methanation.

This study has made it clear that any unnecessary conversion, such as from wood into a higher-quality fuel when process heat is subsequently generated, should be avoided. Besides that, due to cost, electricity from biomass is produced as baseload power. In the future, it is expected that biomass will be increasingly used to meet peak energy demands (e.g., in winter when there is no solar radiation). Moreover, biomass should be used following the principle of circular economy [3,58], even though in Swiss practice, the implementation is sometimes difficult, e.g., cascading the use of wood [59].

This overall view for the canton of Aargau gives an idea of the extent to which the objectives of the Energy Strategy 2050 can be achieved, even if the results cannot be simply transferred to other cantons. The considerations presented here are intended to improve an understanding of the system and to objectify the discussion on energy system transformation. The methods developed can be applied to other regions or countries, provided that there is sufficient data available for this purpose. The study does not in any way suggest that a self-sufficient energy supply should be sought only at the local level. The clear parameters and excellent data availability allowed a theoretical consideration in the sense of a thought experiment. An exchange of renewable energies across cantonal or national borders certainly makes sense.

It is important to consider both the development of the possible energy supply options and changes for consumers. Possible price increases are highly relevant and should be part of further studies. Significant system-related changes are already on the horizon. A future grid will have to manage with a much lower base load. This makes energy storage systems all the more important for balancing the different renewables.

There are currently still efficiency deficits in both energy conversion and consumption, which could be exploited for the transformation of energy systems [22]. The final energy consumed in transport, for example, is predominantly converted into waste heat in combustion engines—even engine power is often irreversibly wasted during braking. Similarly, private households, which use about 75% of their final energy consumption for domestic heating, could halve this consumption through simple thermal insulation measures. The 43% savings potential mentioned in the cantonal energy strategy [22] already takes this into account.

The conversion of the mobility system, including various propulsion technologies, is of central importance for energy system transformation. The major challenge, however, lies not only in replacing combustion engines with alternative energy vehicles but also in the far-reaching consequences for alternative resources, competing demands for use and the effects on the entire energy system. As various studies confirm, fossil combustion engines for private transport are disappearing due to the need to reduce CO_2 emissions [27,60]. This is also linked to the question of future fuel requirements and the necessary resource base for biofuels. The demand for fuel depends primarily on the further development of the engine industry and is already shifting towards electromobility. Developments in alternative transport concepts, such as the "Cargo Sous Terrain" underground tunnel system in Switzerland, are also enabling a shift towards electricity-based goods transport and individual transport. The increased demand for e-mobility and e-transport could significantly reduce overall energy consumption because these technologies use energy more efficiently. In addition, batteries in electric cars could be used for short-term storage for daily electricity peaks from PV energy. If, however, more energy in the form of electricity was needed for mobility purposes, this would require adjustments in production. Transport may consume less final energy, but it needs significantly more electricity. In order to cover the missing total energy demand (2545 GWh) with PV, at least an additional area of 13–17 km^2 of PV systems would have to be installed. If the deficit were to be covered by wood energy, at best, around 1.7 million cubic meters of dry wood would have to be imported, considering the conversion efficiency in SNG. If not imported, this would correspond to around 18% of Switzerland's annual forest wood production, or around three and a half times that of the production from the canton of Aargau [61].

Air traffic will not be electrically possible and will require liquid fuels with high energy density, at least on long routes. These can be produced from biomass or CO_2. Due to the comparatively low conversion efficiency, the production of liquid fuel from woody biomass will tend to take place in large plants (>100 MW). Such plants are unlikely to be realized in Switzerland due to the large biomass resources (or transport routes) required and the cost situation. In the international context, such plants are an interesting option but are very unlikely to be used for a self-sufficient energy supply in the canton of Aargau.

Various simplified assumptions were made for this Aargau study, some of which were based on optimistic conversion efficiencies. It should be mentioned, however, that different boundary conditions could be developed. As shown in the list below, various developments could change the degree of coverage of the canton to a greater or lesser extent compared with the figures presented here, for example if:

- Forest timber is primarily used for material purposes (construction timber, chemicals, etc.)
- The sustainable energetic biomass potential is not fully exploited
- Not all heat sinks for low-temperature heat are equipped with heat pumps
- Part of the wood for energy continues to be used for heat production if, for example, forest owners (especially in remote regions) continue to use their own wood in decentralized small furnaces
- High-temperature heat for industrial processes, which can only be provided by combustion processes, accounts for a non-negligible proportion of the sustainable biomass potential

- Conversion efficiencies of technologies available in the future, e.g., due to additional processing steps for biomass, are lower than expected
- The increase in efficiency is not achieved to the extent demanded by the federal government
- The population grows faster than forecasted.

In addition to these uncertainties, it is also difficult to predict which energy products will be offered and preferred in the future market. In this context, this study made clear that the demand, the development and the actual use of heat pumps are much more important for the overall coverage of the demand than the choice of a specific biomass conversion path.

This study also showed that the sustainable biomass potential can contribute up to 12.7% to the total annual demand. Though small, this is nevertheless a significant share, especially in view of the fact that energy from biomass can react flexibly to demand. The bioenergy market is, especially today, a niche market. Various conversion paths not considered in this study also occur in practice due to residue/biomass-specific properties or ecological and sociological aspects. It can be assumed that these will also be used in the future. A broad technology portfolio can thus certainly have a positive influence on the energetic utilization of the sustainably available biomass.

5. Conclusions

The case study in the canton of Aargau presents the development of energy demand and the potential for renewable energy until 2035. The calculations made it clear that sustainable available renewable energies in Aargau will probably not be sufficient to cover the canton's forecast energy demand for 2035. At best, 74% of the energy required can be provided by renewable energy. With a contribution of max. 12.7% to the energy demand, bioenergy will also not significantly improve this incomplete coverage of energy demand. The calculations also reveal competing demands for use. For mobility and transport purposes, depending on the scenario, at least 26–43% of the total energy demand is not covered. Today as well as in the future, the import of energy sources will be necessary. A self-sufficient energy supply for the canton of Aargau is therefore not possible.

Many decisions still have to be negotiated to shape the energy transformation in Switzerland. Although the transition will mainly take place locally, the results show that energy system transformation cannot only be considered at the local level. Different levels of perspectives are needed as local analyses provide a concrete basis for the energy transition while supra-regional analyses allow overall optimization. A consideration of the overall system on the national and international level is necessary to develop a sustainable and reliable solution. Local strategies are necessary to take regional framework conditions and special features into account. Here, the local-regional view allows a concrete assessment of the possibilities on a quantitative basis. This is not only about the choice of natural resources and how intensively they are to be used for energy supply, but also about prioritizing the technologies and conversation paths. Last but not least, not only do we need to maximize the energy services obtained from each unit of energy, but we probably also need to reassess all energy-consuming tasks in order to reduce overall energy consumption.

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