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Biofuels for road transport: Analysing evolving supply chains in Sweden from an energy security perspective

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Abstract:

The use of biofuels for road transport in Sweden has increased during the past 10 years as policymakers stimulate demand in response to concerns about climate change. Using a supply chain approach, this paper analyses: i) existing biofuel supply chains in Sweden (biogas, biodiesel and bioethanol) in terms of security of supply, and ii) possibilities to achieve synergies between implementation of climate change mitigation practices and security of supply objectives, through increased production and use of biofuels.

We argue that synergies can arise when exposure to upstream market risk decreases, the risk of the feedstock does not correlate with the fuel that it replaces, producers can switch between feedstocks and end user vulnerability to disruptions decreases. In the current Swedish context, the features of the biogas supply chain make it the most beneficial option, followed by biodiesel. In the way it has been implemented, bioethanol is the least favourable option. The paper concludes by outlining how biofuels could contribute to security of supply in the future.

Keywords: Biofuel, Energy Security, Policy Coherence, Road transport, Security of Supply

1. Introduction

Investigating the interactions between climate change mitigation and energy security is a growing field of research [1]. Renewable energy, biofuel in particular, is sometimes depicted in the policy sphere as a means to reduce greenhouse gas (GHG) emissions and simultaneously increase energy security, especially in the transport sector, which is dependent on oil products, see e.g. [2-4]. However, whether or not these two policy areas are synergetic depends on several factors, particularly the individual technological options implemented [5]. This implies that the level of coherence depends not only on the policy objectives, but also the instruments and implementation practices used [6].

Sweden is an example of a country in which policymakers have stimulated use of biofuels in the road transport sector in response to concerns about climate change. This has contributed to increasing the use of biofuels from less than 0.3 TWh in 2000 to 6.95 TWh in 2012 [7, 8]. By 2012, the increase had also enabled Sweden to reach its EU-mandated target of at least 10% renewable fuels in the domestic transport sector by 2020 [3, 9]. Swedish policymakers have the ambition to increase the use of renewables further and make the Swedish road transport sector "independent of fossil fuel" by 2030[1] [10]. However, apart from this providing the possibility to reduce import dependence [11], the interaction with energy security has not been thoroughly assessed.

There are varying perceptions of what energy security symbolises [12-14]. Johansson [15] proposed that interpretations of the relationship between energy and security be classified as relating either to when an energy system is an object and the functionality of the system is to be secured, commonly known as security of supply or security of demand, or to when the energy system is an agent that causes and generates insecurity, for example as a result of a perceived political or economic value. In this study we examined the former, i.e. security of supply. Since coherence between climate mitigation and energy security policies was being analysed, we use the Swedish Energy Agency's definition of security of supply[2], which is: a system that has capacity, flexibility and robustness to reliably meet users demand at an acceptable cost and the capacity of the market, government and users to respond to disruptions in the case of an emergency [16] (our translation from Swedish)[3]. The study focuses on flexibility, robustness and capacity to respond. Sweden's security of supply strategy to date has mainly been to promote market liberalisation [17] and, for crude oil, international cooperation in the case of emergency, e.g. participation in the IEA emergency oil sharing mechanism and collaboration with other EU countries.

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[1] The meaning of "independent of fossil fuel" is not stated explicitly. We interpreted it as the Swedish Transport Administration, reducing the final use of fossil fuels in the transport sector by at least 80% from the current level [87].

[2] Energy security can be approached from different epistemologies. Cherp and Jewell [88] argue that policy concerns should be the starting point when defining energy security. We assumed here that the Swedish Energy Agency's definition reflects Swedish policymakers' concerns.

[3] The adopted definition has similarities with general definitions such as "low vulnerability of vital energy systems" [89].

Energy systems can broadly be described as supply chains consisting of multiple interconnected stages, from resources to final energy use [18]. The aims of this study were to: i) analyse security of supply for existing biofuel supply chains in the Swedish road transport sector and, ii) analyse the potential of biofuels to increase security of supply in the future. When applicable, comparisons were made with the supply chain for oil products, the current dominant alternative for road transport in Sweden, as it offers a point of reference for emerging biofuel supply chains.

2. Method and approach

A strain can impact on any of the supply chain stages, but the consequences depend both on the strain (e.g. type and magnitude) and on the vulnerability of the system to the specific strain. For example, a system can be resilient or have the capacity to adapt to a changing environment while maintaining its functionality [19].

To enable separate studies of the various stages in the supply chain and comparisons of different supply chains, we divided the analysis to reflect the five stages of the supply chain: upstream market, domestic feedstock, domestic production, distribution and final use (see Figure 1). Note that imports can be both feedstock and secondary fuel, but we analysed them in one cluster.

-INSERT FIGURE 1 HERE-

The factors we analysed for the respective stages in the supply chain are outlined below with reference to previous research[4]. Data were taken from government institution reports and statistical databases to obtain information on each part of the supply chain. For the analysis described in section four, we also used data from previously developed scenarios of how the Swedish road transport sector could become independent of fossil fuels. We analysed four different supply chains, at the national level, based on three final energy carriers; biogas bioethanol and biodiesel from fatty acid methyl esters (FAME) and hydrotreated vegetable oil (HVO).

2.1 Imports of feedstock and secondary fuel

Evaluations of the upstream energy market risk typically assess diversifiable and/or systematic risk using either dual-diversity indices [20] or financial portfolios [21, 22]. Sweden does not have a foreign policy-related security of supply policy and the choice of import sources is therefore determined by market factors rather than bilateral trade agreements. Therefore, the main concern regarding oil in the Swedish context is systematic risk, as the upstream market is liquid, the

[4] For an overview of different valuation methods see [90].

commodity is fungible and short contract lengths are used [23]. Reducing the exposure to upstream market risk requires a reduction in imports. Several previous studies have assumed that import dependence is negative for security of supply, see e.g. [24-26]. However, contrary to common belief, the ability to import can be positive or even essential, for example if domestic production is damaged, as was the case during Hurricane Katrina, when the US increased its imports of crude oil [27]. In the present study, import dependence was therefore only used to measure exposure to upstream market risk and the optimal level of energy independence was not assessed. Furthermore, the risk associated with the imported feedstock and secondary fuel was compared with the risk associated with crude oil, since renewables have been proposed as strategy for hedging against uncertain and volatile prices of fossil fuel, see e.g. [28, 29].

2.2 Domestic feedstock

Domestic feedstock was analysed as regards availability. Previous studies, based on fossil resources, have analysed the availability of resources using indicators such as the reserves to production ratios [26]. Energy supply chains that utilise renewable energy are dependent on flows instead of extracting stocks. For example, seasonal variations in crop yield and competition with other sectors, such as food production, may restrict the amount of available resources [30]. A previous study has indicated a low risk for agricultural output for Sweden, measured as yearly variability of agricultural production [31]. Therefore, we did not evaluate the variability. Instead, we evaluated the availability of feedstock as the domestic potential.

2.3 Domestic production

The domestic production infrastructure was evaluated in terms of its capacity (measured as installed domestic production capacity), flexibility (measured as ability to shift between different feedstocks in a production facility) and robustness (measured as the number and diversity of production facilities). Flexible production facilities increase the resilience in a situation with limited availability of feedstock or high prices. The diversity was measured using a Shannon-Wiener Index, i.e. a dual-diversity index [32] (see Appendix for formula). For biogas the diversity of the upgrading facilities was assessed, since there are fewer upgrading than production plants. For bioethanol there are two plants, one with two production units, so we assessed the diversity for production plants and units. Besides providing technical robustness, higher diversity may also be beneficial for the market structure, one of the suggested root causes of energy insecurity [33, 34].

2.4 Distribution

The prospects for producing different biofuels vary in different parts of Sweden [35]. The country has also a low population density, indicating a need for a distribution network. We therefore evaluated the distribution in terms of accessibility to users, measured as the number of filling stations providing the fuel.

2.5 Final use and capacity to respond in emergencies

Previous studies have stressed the importance of incorporating the demand side in the analysis of security of supply since the vulnerability of users to disruptions can differ [36]. Exposure to economic strain has been assessed by measuring the energy intensity of different sectors [36] and welfare effects from volatile prices using (partial) equilibrium models [37, 38]. The outcome from physical disruptions has been analysed with energy system models that primarily analyse resilience of infrastructure [39]. However, the vulnerability of end users to disruptions in fuel supply depends on the existence of alternative options. For example, flexibility has been used to value demand-side vulnerability, measured as the capacity to switch between fuels [40]. Instead, we analysed the capacity to reduce the use of secondary fuels, in the event of an emergency, while maintaining adequate transport services.

3. The current Swedish biofuel system

3.1 Feedstock, production, distribution and use of biofuels

In 2012, the final energy use in the Swedish domestic transport sector amounted to 92 TWh. Around 86 TWh, or approximately 22% of final energy use in the country, was used in road transport, of which biofuels comprised 6.95 TWh. In addition, 1.57 TWh of electricity was used within rail traffic, most of it from renewable sources [7, 8]. Biodiesel is currently the frontrunner among the renewable fuels used in the Swedish transport sector. Its contribution is roughly 44%, followed by bioethanol with around 28%, renewable electricity (i.e. generated by biomass-, hydro- and wind power) with 18%, and upgraded biogas with close to 10% [7]. As illustrated in Figure 2, during the past decade both the balance between the different types of biofuel energy carriers and their combined share has increased.

-INSERT FIGURE 2 HERE-

Gas use as transport fuel increased from around 0.56 TWh in 2007 to 1.43 TWh in 2012. In 2012, there were 242 biogas production facilities in Sweden, producing a total of 1.59 TWh for various uses such as heating, electricity generation and fuel. The majority were municipal wastewater treatment plants (135), followed by landfills (55), co-digestion plants (21), farm plants (26) and commercial plants (5) [41]. However, in 2012 no biogas originating from landfills or commercial plants was used to produce vehicle fuel [41]. Biogas used as vehicle fuel is upgraded in one of Sweden’s 54 upgrading facilities [46]. The upgraded gas can then be used directly, transported by lorries or injected into the gas grid. Half of the biogas produced in 2012 (0.81 TWh) was upgraded and mixed with 0.62 TWh of imported natural gas to supply the vehicle gas demand in Sweden [8, 41]. The current volume share of vehicle gas is approximately 40% natural gas and 60% upgraded biogas [43]. One success factor for biogas has been the possibility to integrate it with the natural gas network that is already in place in some regions of the country. This has made it possible to more than double the use of biogas in the transport sector during the last four years.

Domestic biodiesel supply is based on three major production facilities, two for FAME and one for HVO. There are also six small-scale producers of FAME [47, 48]. Most of the biodiesel is blended and distributed to consumers by existing petrol companies, but some producers of FAME also offer concentrated products to nearby stations [48]. The admixture of bioethanol and FAME in Sweden is currently 5% per volume of fuel, but the Government allows blending up to 10% bioethanol in petrol and up to 7% FAME in diesel since May 2011 [49, 50]. For HVO there is no ceiling.

Regarding bioethanol supply, Sweden has two major production plants. The largest is owned by a farmers' cooperative and has two production units [48]. The smaller plant is owned by an international chemical conglomerate and uses lye from the plant's sulphite process as feedstock [51]. The bioethanol is blended in either high (up to 95%) or low (5%) blends with petrol and distributed across the country by existing petrol companies [48].

3.2 Composition of Sweden's vehicle fleet

The Swedish fleet comprises around five million vehicles, in which the composition is 88.67% personal cars, 11.05% lorries and 0.27% buses when motorcycles, mopeds and other vehicle categories are excluded. The composition of the Swedish fleet, organised per type of vehicle and fuel in the last decade, is presented in Figure 3. Note that the figure only includes vehicles fuelled by petrol, diesel, bioethanol and vehicle gas (i.e. a blend of natural gas and upgraded biogas), as other categories had a low share and limited impact on the relationship between bioethanol and biodiesel fuels during the period 2000-2011 [52, 53]. Interestingly, the graphs show similar inverse trends for the numbers of petrol and diesel vehicles in the data-set in terms of personal cars and lorries. However, for buses the number of diesel vehicles has decreased, the number of petrol vehicles has remained at a low level and the number of gas vehicles has increased [52, 53].

-INSERT FIGURE 3 HERE-

As illustrated in Figure 3, the number of petrol vehicles is decreasing and they are being replaced, illustrating that what is happening is a fuel substitution process in the fleet. This is the result of many policy instruments promoting low-carbon emissions, such as a reduced tax on low blend biofuels and fuel-efficient diesel vehicles, which have been affecting the transport sector in Sweden during recent years [7].

The composition of the Swedish fleet has a direct influence on the biofuels consumed. In the case of biodiesel, the composition of the fleet has influenced increased use of the 5% blend. This reflects both a fuel substitution process in the fleet and an increasing diesel dependency. For bioethanol, the declining numbers of petrol vehicles have redirected the bioethanol delivery pathway. In the past 10 years, the 5% blend was the main way of distributing bioethanol, but lately there has been a switch to E85, a biofuel with 85% denatured ethanol used in flex-fuel vehicles. The share of E85 started to increase in 2005 as a result of the National Climate Policy 2030, which stimulated demand [2, 54]. Another important factor is that the national association for the automobile industry gave its support to the initiative [55]. However, the trend changed in 2009 as consumers reacted rapidly to changes in policy and price fluctuations for fuels. In July 2009, the Swedish government removed the premium given for purchasing a clean vehicle, i.e. fuel-efficient cars with CO_2 emissions not exceeding 120g/km or able to use alternative fuels, and the market response was a sharp decline in sales of flex-fuel vehicles in that year [7]. Biofuel sales are also highly dependent on the relative price of oil products. For example, bioethanol consumption in Sweden is attractive until it costs up to around 74% of the price of petrol per litre [56]. In 2009 this threshold was exceeded (with an average cost of approximately 80% of the petrol price per litre), leading to a reduced bioethanol use in that year. However, this has since stabilised and the current trend is for increasing use of E85.

3.3 Security of supply for current supply chains

3.3.1 Import of feedstock and secondary fuel

Of the biogas used in Sweden in 2012, 93% was produced within the country from domestic resources, i.e. the import dependence was less than 7% (see Table 1). For FAME feedstock equivalent to the production of approximately 0.6 TWh of FAME and 1.5TWh secondary fuel was imported in 2012, bringing the combined import dependence, i.e. imports of feedstock and secondary fuel, to above 86% [57, 58]. For HVO and bioethanol, the combined import dependence in 2012 was 60% and 69%, respectively (see Table 1).

Replacing imports of crude oil with imports of biofuels or of feedstock has not reduced the exposure to upstream market risk but has shifted it from the international oil market to the international agricultural market. At present, imported feedstock and secondary fuel are available in sufficient quantities, but their prices are subject to a number of uncertainties affecting supply or demand, e.g. droughts or floods, increased demand from other sectors and temporary export restrictions [59, 60].

Recent studies in other countries have shown that the increased use of biofuels has increased market interactions between the crude oil, agricultural and biofuel markets, which has resulted in volatility spill-over effects [61]. The covariance of the price movement on these markets limits the possibility to use imported biofuels as a hedge against the fuel price risk of crude oil (see e.g. [38] for an analysis of imported bioethanol and crude oil). Therefore, although imported biofuel can reduce imports of oil, the import risk will not necessarily decrease.

Table 1: Summary of Sweden's biofuel sector for road transport, supply and demand

	Biogas	**Biodiesel**		**Bioethanol**
		FAME	**HVO**	
Import dependence in 2012 (feedstock and secondary fuel) [57]	7%	>86%	60%	69%
Main source of feedstock in domestic production [51, 57]	Residues and waste	Agricultural commodity (rapeseed)	Pine oil	Agricultural commodity (wheat)
Number of domestic production facilities [41, 47, 51, 58]	242	8	1	2
Diversity (Shannon-Wiener Index)[a]	3.70	0.62	0	0.17; 0.72
Estimated domestic production capacity (TWh/year) [41, 47, 51, 58]	1.5	2.2	1	1.57
Produced from domestic raw material (TWh in 2012) [57]	0.75	<0.33	0.54	0.79
Domestic use (TWh in 2012) [57]	0.92	2.48	1.37	2.25
Distribution [58]	Vehicle gas	Pure or low blend (5-7%)	Blended (20-25%) with diesel and FAME (5%)	Blended (5-10%, 75-85%, 95%)
Number of filling stations [48, 62-64]	131	22 (B100)	965	1695 (E85)
Has mainly replaced	Diesel	Diesel	Diesel	Petrol
Main vulnerability and limitations	Only available locally, needs technology transition (gaseous fuel).	Exposed to upstream market risk, limited production flexibility, low accessibility of pure fuel for end users.	Limited availability of feedstock, only one domestic producer.	Exposed to upstream market risk, increased imbalance of oil products (i.e. diesel/petrol), only one major domestic producer.

Average CO_2 reduction compared with fossil fuel [b]	73%	40%	85%	65%

[a] A higher value represents higher diversity. For biogas we calculated the diversity for upgrading units, while the other supply chains were valued on the diversity of the production capacity, see Appendix A for calculations.

[b] Emission reductions are reported by distributers for concentrate in comparison with fossil fuels according to EU Directive 2009/28 [57]. The values constitute an average for all fuel sold in each category in Sweden during 2012. The values differ for different production systems and calculation methods, see e.g. [65, 66].

3.3.2 Domestic feedstock

There is a diverse range of potential feedstock available for use in the Swedish transport system, ranging from locally grown bioenergy crops to organic waste and other second generation technologies.

The biogas is mainly produced from sludge, waste and residues with limited economic value [57]. The domestic potential from waste and residues is an order of magnitude higher than the current use of biogas [67]. The Swedish HVO producer uses local pine oil, a residue from the pulp and paper industry. The production of pine oil in Sweden is currently three-fold (equivalent to 1.3-1.75 TWh after conversion losses) the amount used to produce HVO, but the remaining share is currently used for other purposes [51].

The bioethanol and FAME are produced from agricultural crops, mainly wheat and rapeseed, respectively. The availability of these crops therefore depends on the area of land used to grow them in each year, the yield per unit area and competing demand, primarily for food and feed production.

3.3.3 Domestic production

The current market for oil products is dominated by one major supplier, which controls 80% of Sweden’s refinery capacity and is one of the largest owners of fuel stations [68]. Production of biofuels has typically lower economies of scale than production of conventional fossil fuels, as the feedstocks are more bulky, less energy-dense and more expensive to transport over longer distances [69, 70]. This has provided an opportunity for new actors to enter the market, increasing the number of production facilities and possibly the competition between actors.

The estimated domestic production capacity of biogas is 1.5 TWh/year [41]. However, not all of the biogas produced is available as vehicle fuel, since there are technical limitations and demand from other sectors. The production facilities are characterised by high flexibility as, although they generally use waste and residues, they generally have the capacity to switch between different substrates. The diversity of the upgrading capacity (3.70) is higher than the equivalent production diversity for the other supply chains, indicating a robust production system (see Table 1).

The domestic production of FAME and HVO has low flexibility, while the diversity is also rather low. In the case of FAME, this can be explained by a low balance in production capacity among the facilities and in the case of HVO by the fact that there is only one producer.

The larger of the two Swedish bioethanol plants mainly uses wheat, but has the flexibility to use other cereals as well, e.g. barley and rye. The value of diversity differs (0.72 or 0.17) depending on whether the diversity of the two facilities or the three production units is assessed. This indicates that a strain would have a larger impact on the supply if it affected the larger plant than if it only affected the largest production unit.

3.3.4 Distribution

The relationship between oil products and biofuels is especially noticeable in terms of distribution and market integration, as policymakers have chosen both to integrate biofuels into the existing system, with low-blend fuel, and to set up new infrastructure for distribution. To promote the distribution of biofuels, the Swedish government issued a law in 2006 that made it mandatory for fuel stations selling more than 1000 m^3 annually to provide at least one fuel with a high biofuel content [71]. Some small and medium-sized stations have had difficulties meeting the up-front cost. This has contributed to an on-going trend for closures and the number of fuel stations has decreased from 3816 in 2006 to 2786 in 2012 [68], making fuel less accessible for consumers in rural parts of the country. A majority of the new pumps are for bioethanol (1695). HVO is only available in a mix with FAME and diesel, but can be used in ordinary diesel vehicles. Biogas and pure FAME are only available in some regions of the country.

3.3.5 Final use and capacity to respond in emergencies

A previous report on oil use in the Swedish transport sector estimated that up to 30% of the oil demand could be eliminated within 1-6 months if substantial demand-side management policies were put in place, e.g. lower speed limits, fuel rationing and promoting a modal shift in passenger transportation [72]. The report also stated that the policies would mainly reduce the demand for petrol used for passenger transportation. Reducing the demand for diesel, while maintaining adequate energy services, is more difficult, since sectors that use diesel (e.g. agriculture and distribution logistics) have fewer alternative options. This conclusion is consistent with observations made by the IEA [73]. Hence, Sweden is more vulnerable to shortage of diesel than petrol. Furthermore, several components of the bioenergy system are highly dependent on road transport and heavy-duty vehicles [7], meaning that a shortage of diesel could affect Sweden's bioenergy production capacity.

As lorries and personal cars have shifted from petrol to diesel, see Figures 2 and 3, the market is moving towards an oversupply of petrol and undersupply of diesel, a situation that is similar in the European region and is inducing stress on the market for diesel [74]. Stricter requirements on the sulphur content in bunker fuel used in the Baltic Sea and North Sea are coming into force in 2015 [75]. This will increase the demand for diesel in the shipping sector in coming years.

Since Sweden is more vulnerable to shortage of diesel than petrol and the market for diesel is tighter, from a security point of view it would be more beneficial to decrease the demand for diesel and/or increase the domestic supply of its substitutes, rather than seeking to decrease the demand for petrol. Biodiesel (HVO and FAME) have been the best option to date from this point of view, followed by biogas. In the way it has been used historically as a petrol substitute, bioethanol is the least favourable option.

3.3.6 Summary and interaction with climate change mitigation objectives

The biofuel strategy adopted in Sweden has mainly consisted of stimulating demand and integrating the new renewable energy carriers with the existing infrastructure used for oil products. The result has generally been a fuel switch, as illustrated by imported fuels and feedstock and low blends with oil products. This has partly shifted the risk exposure from the oil market to the agriculture market, which in turn is exposed to the oil market and to other risk factors.

The supply chains analysed (biogas, FAME, HVO and bioethanol) have different strengths and drawbacks. It is beneficial for security of supply when the production can utilise predictable flows of domestic waste and residues and when the production is flexible, the market is diverse and the fuel substitutes for diesel. This is mainly the situation for biogas and partly for domestic biodiesel from HVO. However, the share of these fuels in the Swedish fuel mix is still minor and HVO is only produced in one facility in Sweden. Furthermore, upgraded biogas is only available in some regions of the country. FAME is mainly imported, as feedstock or secondary fuel, but it reduces some of the imbalance between petrol and diesel. Bioethanol is currently the least favourable option as the feedstock is imported, the risk correlates to that for oil and it replaces petrol. A summary of the security implications of the different bioenergy options can be found in Table 1.

As a consequence, in terms of coherence between implementation practices of climate change mitigation policies and security of supply objectives, biogas provides strong synergies. HVO also provides synergies. This is partly because it is generally preferable to utilise residues and waste in order to reduce GHG emissions, see e.g. [76, 77]. In comparison with the other biofuels, FAME has a higher import share and results in lower emissions reductions. Overall, bioethanol shows weak synergies and in some aspects even a trade-off, since the supply chain is exposed to the upstream market risk of the agricultural market; there are two production facilities in Sweden, but almost all bioethanol is produced in one of these and ethanol increases the imbalance in supply and demand for petrol and diesel. However, bioethanol is the most widely distributed biofuel in Sweden.

4. Future developments in the biofuel sector

4.1 Development trends in Swedish demand for biofuel

The transport sector in Sweden has a special role in that while consuming only approximately 24.1% of total energy, it is responsible for approximately 45.3% of national GHG emissions [78]. Measures and interventions in the transport sector therefore also have a large impact on the national GHG balance. In 2012, the use of biofuels in Sweden reduced its emissions of GHG by approximately 2.3% [57, 79]. Increasing the share of biofuels or having a supply mix that provides greater reductions would increase this further. For example, a biofuel supply mix that utilises waste, residues or lingo-cellulosic feedstock would reduce emissions more than current technologies, see e.g. [70, 80, 81].

Assuming a business as usual (BAU) growth, the final energy use in the Swedish road transport sector will account for approximately 96 TWh in 2020 and 85 TWh in 2030, as it is assumed that vehicles in general will become more energy efficient [82-84]. In addition, a recent study presented two new scenarios that involve substantial changes in the Swedish energy mix used in the domestic transport sector [82]. The first scenario, Efficient (EF), assumes that the share of oil products will decrease from 90% to 40% of the total energy use in the entire transport sector. Concerning road transport, the share of oil products will decrease to approximately 20% and the energy use would be cut by almost 56% compared with the reference BAU scenario. The second scenario is based on a fuel switching (FS) approach, in which it is assumed that vehicles have moderate improvements of efficiency. In this case, it becomes crucial to increase the amount of biofuels and electricity in order to achieve a similar reduction in the demand for oil products as in the previous scenario. In that scenario, biofuels provide 80% of the total energy used in road transport [82]. Table 2 presents the potential scenarios in 2030 and the contribution per type of fuel.

Table 2: Scenarios for the year 2030 and the bioenergy contribution (TWh) to Swedish road transport per type of fuel. Adapted from [82].

Energy carrier	***BAU***		***Efficient (EF)***		***Fuel switching (FS)***	
Bioenergy	20.2 TWh	24%	25.8 TWh	69%	39.7 TWh	80%
Bioethanol	**7.3 TWh**	**9%**	**9.4 TWh**	**25%**	**14.4 TWh**	**29%**
Upgraded biogas	**4.0 TWh**	**5%**	**5.1 TWh**	**14%**	**7.8 TWh**	**16%**
Biodiesel	**8.9 TWh**	**10%**	**11.4 TWh**	**30%**	**17.5 TWh**	**35%**
Fossil fuels	64.8 TWh	76%	7.7 TWh	21%	4.5 TWh	9%
Electricity[a]	0.0 TWh	0%	3.6 TWh	10%	5.4 TWh	11%
Total	**85.0 TWh**	**100%**	**37.1 TWh**	**100%**	**49.6 TWh**	**100%**

[a] The electricity mix in Sweden in 2012 was: renewables (60%), nuclear (38%) and fossil (2%) [7].

As Table 2 also shows, biofuel options would become more balanced as their shares would become more evenly distributed. These trends are illustrated in Figure 4, where bars represent the energy use in the Swedish road transport sector in TWh and the values are displayed on the left-hand *y*-axis. Highlighted bars illustrate the trends and their respective estimated values for 2020 and 2030. Lines correspond to the energy amount provided in TWh per bioenergy carrier and are displayed on the right-hand *y*-axis.

-INSERT FIGURE 4 HERE-

4.2 Biofuel supply and implications for security

Increased use of biofuels may develop in various directions, as illustrated in Table 2. Scenarios and forecasts of domestic biofuel supply in Sweden 2020-2030, vary with high estimates in the range 30-35 TWh annually by the end of the period [11, 51, 85].

Assuming that 35 TWh are produced from domestic feedstock in 2030, the Swedish road transport sector would have a net import dependence for energy of 59% in the BAU scenario, 6% in the EF scenario and 29% in the FS scenario. This illustrates the importance of addressing both supply and demand to achieve reductions in imports. The numbers also highlight that domestic biofuels could supply a large share of the energy used in the road transport sector. Furthermore, some studies expect that the production of biomass in Sweden will increase in the future as climate change increases the global temperature, thus increasing the potential supply [86].

The domestic biofuel sector could be diversified in terms of producers, feedstock and energy carriers. The technical potential for biogas from waste and residues is estimated to be 16 TWh, of which 8 TWh is technically realistic and economically feasible [67]. If dedicated biogas crops were to be used this value would increase. The potential for biodiesel and bioethanol depends less on residues and more on how much of the land available is used for energy purposes and development of second-generation biofuels. A study of planned and potential expansion of first and second generation biofuel production in Sweden produced high-range estimates of 5 TWh bioethanol and 5 TWh biodiesel by 2030. It was also estimated that the contribution from dimethyl ether (DME), a fuel that can be used in modified diesel engines, could be up to 6 TWh [51]. Assuming that a typical large-scale second-generation biofuel plant has an annual capacity of 1.5 TWh (see e.g. [80]), this would require at least 10 production plants. In comparison, Sweden currently has three oil refineries. Increasing the number of production facilities would increase the reliability of the entire system, provided that failure rates of components are the same and that such failures do not trigger cascading effects. It would also reduce the vulnerability to unforeseen events, such as attacks.

A biofuel supply mix that utilises waste, residues or lingo-cellulosic feedstock can employ different technologies and some of its inherent features could reduce root causes of insecurity, such as concentration of resources and inadequate market structure. Furthermore, an increased number of technologies, e.g. a multicarrier energy system, could be negative for security of demand if it is more expensive and creates an uncertain investment environment for producers and distributors, as illustrated by the recent closures of filling stations in Sweden (see section 3.3.4). This could reduce investment in upstream capacity. Investment uncertainty and financial barriers could partly be compensated for if policies adopt longer time horizons and vehicles could shift between several fuels, integrating and expanding the size of the downstream market for different energy carriers.

The future development of biofuels provides possibilities both to reduce emissions of GHG and increase security of supply. However, achieving the two policy objectives simultaneously may require policymakers to focus on the entire supply chain, i.e. both supply and demand, which could require a trade-off with cost efficiency objectives, at least in the short term.

5. Concluding remarks

The ongoing development of the Swedish biofuels supply chain has affected the country's security of supply by diversifying supply of feedstock, the downstream market and use of biofuels. However, this trend may continue in various directions, since it depends on infrastructure and management capability related to local production, especially second-generation biofuels, in order to not rely almost entirely on imports. The current Swedish biofuel strategy has only had limited effects on reducing the system's vulnerability and the root causes of insecurity, because the change has comprised a fuel switch rather than transformation of the energy supply chain. Sweden may be able to alter that by adopting a strategy based on domestic biofuel production. As a result, it would foster the possibility for new actors to enter the market. This could change the structure of the fuel market and make it more diverse. In this context, our analysis shows that major synergies with supply security could be achieved by increasing:

- The use of domestic waste and residues as feedstock
- Fuel efficiency in the transport sector
- Market and technical diversity
- Diesel substitutes

These increments could make the domestic road transport system more resilient to exogenous change in terms of fuel availability and increasing or volatile fuel prices. For example, a reduction in demand for diesel or increasing availability of viable substitutes could reduce some of the stress originating from the current market imbalance. However, the outcome may require a trade-off with cost-efficiency objectives in the short term. One available short-term option is to increase low blends of biodiesel and/or shift incentives for personal cars from diesel to flex-fuel/E85. In the long run, reducing the overall demand for diesel could be achieved by a modal shift from lorry to train freight or through measures to avoid transportation.

Lastly, this paper focused solely on biofuels. Other options to decrease emissions from the Swedish road transport sector, e.g. electric vehicles or plug-in hybrids, could also affect security of supply and should be analysed in further research.

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Appendix A. Calculations of diversity

The following data were used to produce assessments of diversity (section 3.3.3).

Shannon diversity Index was calculated according to Eq. (A1) [32] as:

$$H' = -\sum_{i=1}^{R} p_i * \ln p_i \quad \text{(A.1)}$$

For FAME, HVO and bioethanol, *i* corresponds to the share of domestic production capacity of facility *i*. For biogas, *i* corresponds to the share of domestic upgrading capacity for facility *i*.

Capacity for upgrading units (p_i) for biogas (Nm3/h) is [46]: 660, 80, 280, 300, 500, 350, 400, 400, 450, 250, 1400, 140, 250, 330, 20, 600, 250, 650, 25, 250, 800, 600, 240, 200, 500, 360, 200, 1600, 650, 250, 450, 200, 500, 20, 750, 800, 80, 80, 130, 2000, 600, 620, 800, 1000, 200, 1200, 550, 2000, 700, 300, 300, 300, 800, 350, 300

Production capacity (p_i) for FAME (GWh/year) is [47, 48]: 1700, 500, 9, 9, 2.75, 2.75, 2.75, 2.75

Production capacity (p_i) for HVO (GWh/year) is [51]: 1000

Production capacity (p_i) for bioethanol (GWh/year) is [51]: 1140, 395, 65

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