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The dynamics of the Swedish biofuel system toward a vehicle fleet independent of fossil fuels

Alessandro Sanches-Pereira*, Maria F. Gómez

Department of Energy Technology, KTH Royal Institute of Technology, Brinellvägen 68, 100 44 Stockholm, Sweden

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The objective of this study is to present an analytical framework monitoring the development of the Swedish biofuels system, to evaluate its impacts on the achievement of 10% of renewable fuels by 2020, and to identify development patterns in order to establish a vehicle fleet independent of fossil fuels by 2030. The methodological approach relies on systems thinking approach and uses causal loops diagram as a guide to our analysis. The results show that policymakers have to decide among different pathways of growth based on internal- and external-resources of the Swedish biofuel system as well as to apply either supply or demand pressures onto the system in order to accomplish a vehicle fleet independent of fossil fuels by 2030.

1. Introduction

The development of renewable transport fuels in Sweden has been on the country's agenda since the first international oil price shock in 1973, which has helped to establish the building blocks for the growing renewable fuels in the country, especially biofuels (Hillman and Sandén, 2008; Ulmanen et al., 2009; McCormick et al., 2012). In 2012, the final energy use in the Swedish domestic transport sector amounted to around 92 TWh, of which renewable fuels comprised 8.52 TWh. The share of renewables in the domestic transport sector has more than tripled in the last decade, from 2.5% in 2000 to approximately 9% in 2012. In a business as usual scenario (BAU), Sweden may exceed its 2020 target of 10% renewable fuels by 2%, with renewables accounting to approximately 12 TWh (Swedish Energy Agency, 2009, 2011; 2012a, 2012b, 2012c, 2013a; Newman, 2010; Svenska Bioenergiföreningen, 2012, 2013). Yet, the Swedish government's vision is more ambitious and the country is determined to have a vehicle fleet independent of fossil fuels by 2030, which means decreasing from today's share value of 91% fossil fuels to less than 50% in the final energy use for domestic transport in the country by 2030 (Government of Sweden, 2010). This study aims to present an analytical framework to: (i) monitor the development of the Swedish biofuels system, (ii) evaluate its impacts on the achievement of the mandate of 10% renewable fuels by 2020, and (iii) identify development patterns so as to establish a vehicle fleet independent of fossil fuels by 2030.

The study relies on secondary data collected from governmental institutions and statistical databases. Academic publications, reports from important stakeholders, and personal communications are used to complement and validate processed information, which is fed into the *Consideo Modeler* software platform to design causal loops. Through this, we intend to match the potential energy use in the Swedish domestic transport sector with the country's desired targets. Our methodological steps include (i) identification of the development trend in the current Swedish biofuel system using forecast analysis against chosen scenarios, (ii) calibration of target scenarios using cross-analysis between forecasting and backcasting analysis, (iii) description of the Swedish biofuel system using a cause and effect model, and (iv) identification of reinforcing or balancing effects within the Swedish Biofuel system.

2. The Swedish biofuel system

Currently, biodiesel is the frontrunner among the renewable energy carriers used in the Swedish transport sector. In 2012, its contribution to the renewable energy mix used in domestic transport is approximately 44%, closely followed by bioethanol with around 28%, renewable electricity (i.e., generated by biomass-, hydro- and wind-power) with 18%, and upgraded biogas with near 10% (Swedish Energy Agency, 2009, 2011; 2012a, 2012b, 2012c,

* Corresponding author.
E-mail addresses: perei@kth.se, lelle9@me.com (A. Sanches-Pereira).

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2013a, 2013b; Svenska Bioenergiföreningen, 2012, 2013). The total use of renewable fuels has increased from 2 TWh in 2000 to more than 8 TWh in 2012. However, the development trends vary for the different energy carriers reflecting changing directions in Swedish policies. Understanding the allocation of renewable energy carriers can provide an outlook of their role in meeting the mandate of 10% renewable fuels in the Swedish domestic transport sector by 2020. One interesting fact observed in the current contribution of renewable fuels is that renewable electricity has maintained its amount of energy provided rather stable (e.g., oscillating around 1.5 TWh) despite losing its position as the key renewable energy carrier during the period between 2000 and 2012. In fact, renewable electricity provides slightly less energy today than it did in 2000. Nevertheless, electricity is expected to gradually regain its position as an important energy carrier in the long run (e.g., 2050), particularly in passenger cars (Olsson and Hjalmarsson, 2012).

According to Sköldberg et al. (2010) the amount of electricity needed by 2030 to supply a growing fleet of electric vehicles (EVs) would increase from today's 3 TWh up to 9 TWh (Sköldberg et al., 2010). Also, the expansion of EVs pushes the development of conventional vehicle toward more efficient engines with lower emissions. This creates a competition where everyone would like to offer an attractive product. For example, "green cars" in Sweden currently have emissions bellow 120 g of CO_2 per kilometer and they are expected to get even lower (e.g., "super-green cars" have emissions bellow 50 g). Assuming a BAU scenario – in which the final energy use in the Swedish domestic transport sector would account for about 108 TWh by 2030 and that EVs are not going to stimulate electricity generation in the median run (e.g., before 2030) – and supposing the share of renewable electricity is kept under current values, the amount of renewable electricity by 2030 would be around 1.6 TWh or 17% of the renewable energy used for domestic transport in Sweden (Sköldberg et al., 2010). Hence, the remaining demand of 83% would need to be covered by biofuels, which corroborates their role as key energy carriers in achieving a vehicle fleet independent of fossil fuels.

Under a more optimistic perspective, Sköldberg et al. (2010) present two new scenarios that involve substantial changes in the Swedish energy mix used in the domestic transport sector. The first scenario, called Efficient (EF), assumes that vehicles in general are more energy efficient by 2030. It also assumes that the amount of fossil fuels decreases from 90% to 40% of the total energy use in the transport sector in the same period. In this context, the amount of energy used in Sweden would be cut by almost 50% when it is compared to the reference scenario BAU. This means that roughly 30 TWh or 54% of energy use in Swedish domestic transport sector would be covered by renewable energy, in which biofuels still remain the key energy carrier with about 88% share of the total renewable energy used in the country's domestic transport. The second scenario is based on a fuel switching (FS) approach, in which it is assumed that future vehicles keep the current efficiency. In this case, it is crucial increasing the shares of biofuels and electricity in order to reach the same level of fossil fuel use as in the EF scenario. Again, biofuels play a significant role toward the vision of achieving a vehicle fleet independent of fossil fuels by 2030. In this scenario, biofuels would account to about 89% share of the total renewable energy used in the domestic transport (Sköldberg et al., 2010). Table 1 summarizes these potential scenarios for 2030.

Each one of these potential scenarios ratifies biofuels as important energy carriers that can help Sweden to achieve a vehicle fleet independent of fossil fuels. It is important to notice that none of these scenarios provides information about the contribution of bioenergy carriers in the final supply. Therefore, there is no indication on how diversified and well-distributed could be the contribution of bioenergy carriers in the system in order to build up security and reliability levels. It should be noted that in an increasingly carbon-constrained world, we assume multi-carrier energy systems based on renewables as more reliable energy systems than fossil fuel based systems. In addition, its flexibility would increase the likelihood of meeting the country's desired target of a vehicle fleet independent of fossil fuels.

Table 1
Potential scenarios of energy consumption for the Swedish domestic transport sector in 2030.

Energy carrier	BAU		Efficient (EF)		Fuel-switching (FS)	
Fossil fuels	97.4 TWh	90%	21.9 TWh	40%	21.9 TWh	31%
Biofuels	7.9 TWh	7%	25.8 TWh	47%	39.7 TWh	56%
Electricity	3.2 TWh	3%	7.0 TWh	13%	9.1 TWh	13%
Total	108.5 TWh	100%	54.7 TWh	100%	70.7 TWh	100%

2.1. Swedish biofuel system's dynamics

In other to understand the contribution of bioenergy carriers, our study uses a system thinking approach. System dynamics thinking began in the mid-1950s as a tool to improve understanding of complex industrial processes. This approach utilizes drivers within the system, which are represented as information–feedback processes, to model a feedback structure closely tied to system performance. Since then, it has been applied to solve a wide range of problems, from industrial and organizational to policy-oriented issues (Sterman, 2000; Bush et al., 2008).

Bioenergy systems present a higher complexity than fossil fuel systems since they have a larger stakeholder networks and industry associations (Börjesson et al., 2009). Bioenergy systems can be seen as a classic system dynamics case and their problems tend to share the following four important characteristics (Bush et al., 2008):

- They are dynamic, which implicates change over time.
- They involve multiple stakeholders with diverse interests, ranging from farmers, entrepreneurs, and consumers to policymakers, whose interactions can impact the system's overall performance.
- They present interdependencies with different systems and processes, which are critical to their overall performance (e.g., competition among food, fiber and fuel production).
- It can be challenging to identify communication issues, structural components, and leverage points.

Therefore, using a system dynamics model provides useful information about the future development of the Swedish biofuel system. It can help to identify underlying structural components and its interactions, which could be used as leverage points to steer and control the system's development. Fig. 1 illustrates the development of bioenergy contribution per type of biofuel to the Swedish domestic transport in the last decade, which is the result of the involvement of both the national and local levels in breaking dependence on oil (Swedish Energy Agency, 2009, 2011, 2012a, 2012b, 2012c, 2013a, 2013b; Svenska Bioenergiföreningen, 2012, 2013; McCormick et al., 2012). Bars indicate the amount in TWh of renewable energy used in the domestic transport sector from 2000 to 2012. Lines represent the biofuel share in percentage or its contribution to the energy supplied in the same period.

Fig. 1 shows that the increment of renewable energy between 2000 and 2012 relies entirely on the bioenergy contribution. It also shows that bioethanol was the key bioenergy carrier in 2000 with 60% contribution in the total bioenergy used (e.g., 0.26 TWh) by the Swedish vehicle fleet in that year. Yet, the behavior of the system

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