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# Energy performance indicators as policy support for public bus transport – The case of Sweden

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## Abstract

The share of renewable fuels in Swedish public transport is steadily increasing, in line with European energy and climate goals as well as a national goal of a fossil-free vehicle fleet by 2030. However, the progression towards this goal is quite different among the Swedish regions, and efforts have been made on a national level to compare the public bus transport systems and provide a foundation for policymaking. This paper investigates different ways of assessing and presenting the energy performance of public bus transport systems. The analysis includes use of renewable and fossil fuels as well as energy efficiency and its underlying factors. Various energy performance indicators are presented and discussed with regards to practical implications and applicability for policy support.

A life cycle perspective on fuels (“well-to-wheel”) is found to have clear advantages when it comes to global reductions of fossil energy use and emissions. This requires detailed information about the fuel use, which is not always the case with the existing reporting system. Setting the energy use in relation to number of passengers transported rather than just the distance covered would better reflect the function of the transport system, but is also more uncertain with the current data available.

**Keywords:** *Energy efficiency, public transport, life cycle perspective, well-to-wheel, energy performance indicators, policy support*

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## **Nomenclature**

EU	European Union
FAME	fatty methyl ester
GHG	greenhouse gas
HVO	hydrated vegetable oil
JRC	European Joint Research Center
PE	primary energy
pkm	passenger-kilometre
RME	rapeseed methyl ester
SCB	Statistics Sweden
SKL	Swedish municipalities and regions
TTW	tank-to-wheel
vkm	vehicle-kilometre
WTT	well-to-tank
WTW	well-to-wheel

## 1. Introduction

The transport sector is one of the main contributors to global warming and air pollution, and is central in the work towards reduced greenhouse gas (GHG) emissions, improved energy efficiency and an increased share of renewable energy sources in the European Union (EU) (European Commission, 2016, 2014, 2011, 2009, 2008). The overarching goal for the EU is to reduce GHG emissions from transports by 60% compared to 1990, while also allowing the sector to grow (European Commission, 2011). Within the framework of the European goals, the individual EU member states decide on national energy and environmental goals and policies for the transport sector.

Sweden has set the goal to reduce the greenhouse gas emissions from the transport sector by at least 70% from 2010 to 2030, and that the whole transport sector will be completely free from fossil GHG emissions by 2045 (Swedish Energy Agency, 2017). As public transport is working for public authorities, it can much easier be influenced through public policy and available instruments such as public procurement than the private car that is dominating road transport in Sweden and other EU countries (Aldenius and Khan, 2017; European Commission, 2018). Rytterbro et al. (2011) investigated the relation between renewable energy targets for the transport sector and current planning horizons, concluding that long-term planning involving political and commercial actors on different levels is required to achieve such targets.

The use of biofuels in Sweden has steadily increased over the last 20 years; an increase which to a large extent has been covered by imported fuels (Martin et al., 2016). In 2016, Sweden had the highest share of renewable fuels in road transport among the EU countries: 16.6%, not including electricity; compared to the EU average at 4.6% (Eurostat, 2017a). Currently, a large share of the renewable fuels that are used in Sweden are imported. The country was in 2016 the largest net importer of biodiesel in Europe (Eurostat, 2017b, 2017c). Estimations of the potential future production of biofuels in Sweden suggest a significant increase compared to current levels (Ahlgren et al., 2017; Börjesson et al., 2013). Ahlgren et al. (2017) concluded that it is possible for Sweden to become self-sufficient in renewable fuels by year 2030 without increasing the use of agricultural land, although this would require a significantly increased production as well as more efficient use of the fuels.

In recent years, an increasing number of studies on vehicle energy performance consider energy use in a life cycle perspective, rather than just the energy content of the fuel. In Sweden, Börjesson et al. (2010) calculated the life cycle energy use and emissions from renewable fuels, including energy used for production and distribution of fuels as well as the final energy use in the vehicle. Energigas Sverige, Region Skåne and Swedegas urged the importance of accounting for environmental impacts beyond tailpipe emissions in procurement of public transport in their report "Proposition for a national biogas strategy" (Energigas Sverige et al., 2015). In a more international context, the European Joint Research Center (JRC) have produced reports on the energy use and emissions "well-to-wheel" (WTW) as well as "well-to-tank" (WTT) of renewable and fossil fuels (Edwards et al., 2014a, 2014b). The life cycle or WTW perspective on fuels and electric powertrains was also lifted by Moriarty and Honnery (2012) and has been applied in case studies on China (Ou et al., 2010), USA (McKenzie and Durango-Cohen, 2012; Xu et al., 2015), Finland/USA (Lajunen and Lipman, 2016), Finland/France/Germany (Nylund and Koponen, 2012) and Switzerland (Yazdanie et al., 2016), often concluding that gas or electric engines can significantly reduce the environmental impact compared to conventional diesel engines. In a study on the WTW energy use and emissions of buses with different fuels, Wang et al. (2015) concluded that flexibility is important to adapt the fuel mix to variations in economic and environmental conditions over time.

The present paper takes on the question of how to evaluate and compare the regional bus transport systems, in order to steer towards an energy-efficient, fossil-free and environmentally sustainable transport sector. Various energy performance indicators for public bus transport are suggested and discussed with regards to applicability for policy support, relevance for assessment of energy efficiency and environmental impact and practical feasibility in data collection. More specifically, different ways of assessing and presenting the use of fossil and renewable fuels as well as the energy efficiency of public bus transport are discussed. The analysis is based on data for regional public transport systems in Sweden. We also make efforts to explain regional differences in Swedish public bus transport systems using statistics and literature.

## 2. Public bus transport in Sweden

The public transport system in Sweden is organised on a regional level by 21 administrative regions (Figure 1). The role of public transport in the work towards reduced emissions and use of fossil fuels was investigated in 2013 by the Swedish public transport organisations in collaboration with the organisation for Swedish municipalities and regions ("Sveriges Kommuner och Landsting", SKL). The common environmental programme for the public transport sector (*Branschgemensamt miljöprogram 2.0, 2013*) identified key areas of environmental impact from public transport and set up goals regarding reduced used of fossil fuels, reduced CO<sub>2</sub> emissions and increased energy efficiency per passenger-km until 2025. The declared ambitions of the programme were to achieve great reductions in environmental impact from the whole transport sector by making public transport more efficient and increasing its market share compared to private transport.



Figure 1 – Map of Sweden, showing the 21 administrative regions (adapted from (SCB, 2007))

In conjunction with this, SKL have produced a series of reports presenting statistics on the regional public transport systems in Sweden, with the intention of enabling comparison between the regions (Rhudin et al., 2017). These reports are largely based on the national database FRIDA, where representatives for the regional public transport companies report the status of their vehicles on a yearly basis, including aspects on environmental performance, safety and accessibility (Nordic Port, 2017). Regarding environmental performance, the data in FRIDA covers energy use per vehicle type (bus, ship, car, tram, train) and propulsion system (diesel, ethanol, vehicle gas, electricity, MDE, gasoline), vehicle-km per fuel and vehicle type, and emissions of CO<sub>2</sub>, NO<sub>x</sub> and particulates. Out of these, the reports from SKL include two indicators, for bus transport only: fuel use (kWh) per vehicle-km and the share of the total fuel used (in energy) that comes from renewable sources. The choice of these indicators is motivated in the reports by stating that they are correlated and should be analysed together, as renewable fuels tend to give a lower engine efficiency and can thus increase the fuel use (Rhudin et al., 2017). The charts from the SKL report are reproduced in Figure 2, using data from FRIDA (Nordic Port, 2017).

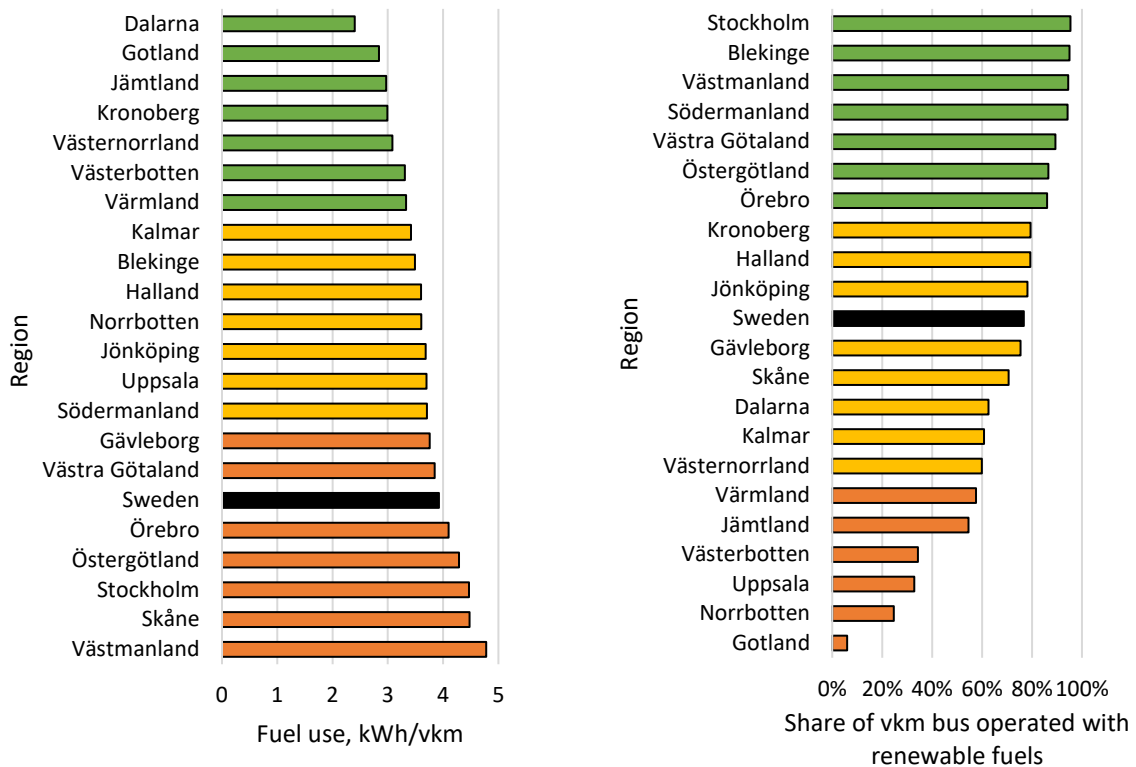


Figure 2 – Fuel use per vehicle-km bus transport (left) and share of vehicle-km bus transport operated with renewable fuels (right) in Swedish regions 2016, as presented in the national public transport report (Nordic Port, 2017; Rhudin et al., 2017)

Regional differences in energy efficiency found in the statistics are explained by Rhudin et al. as a result of the fact that some regions have a higher share of city buses, which consume more fuel than buses outside the cities due to more frequent starts and stops (Rhudin et al., 2017). This is also supported by results from de Abreu e Silva et al. (2015). Ma et al. (2015) found that driving style can affect the fuel consumption in city buses by 10-20%.

Xylia and Silveira (2017) reported on the fuel situation in public bus transport in Sweden in 2014, using data from the FRIDA database. They found no significant difference between the regions regarding the use of renewable fuels in relation to population density or transport volume. Instead, they concluded that the most important factors for increasing the use of renewable fuels are political will, policies and strategic planning. Their study included a survey where public transport authorities in Sweden were asked to rank the most attractive renewable fuel alternatives for the near future. Here, electricity came out as the most attractive option, followed by biogas and RME in shared second place and HVO as number four.

### 3. Method

In this paper, the energy performance of public bus transport systems is addressed through quantitative secondary data analysis. By putting together official data and statistics with assumptions suggested by national or European research centres, alternative energy performance indicators are created and compared to current, official figures. The use of renewable fuels is reviewed on a detailed level, dividing the energy use into different types of fuels, and the resulting reductions of fossil fuel use and well-to-wheel greenhouse gas emissions are investigated. The performance indicator for energy use in public bus transport is varied in two dimensions: tank-to-wheel or well-to-wheel energy use, and energy use per vehicle-kilometres or per passenger-kilometres. Variations in fuel efficiency

between different regions is checked for correlations with surrounding parameters, in an attempt to explain these regional differences.

Data on fuel properties used in energy calculations are given in Table 1. Factors for calculation of well-to-wheel energy use and GHG emissions were derived from the JRC well-to-tank report (Edwards et al., 2014b, 2014c) and the raw material mix in biofuels used in Sweden (Westin and Forsberg, 2015). The respective fossil energy use for production of fuels was added to the fossil energy content of the fuels to get the non-renewable primary energy (PE) use. GHG emissions include CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O from production of the fuel in to combustion the engine. Energy contents of fuels were set in accordance with the values used in FRIDA (Nordic Port, 2017; *Emissionsberäkningar i FRIDA*, 2017). WTT pathways for the fuels are described by Edwards et al. (2014c) using the denotations given in the second column of the table. Data for the fuel pathways were set by Edwards et al. using Monte Carlo simulation, considering a range of variability for each phase in the life cycle (Edwards et al., 2014c). In this paper, the median values for PE use and GHG emissions presented by Edwards et al. (2014c) are used, and the 20<sup>th</sup> and 80<sup>th</sup> percentiles (P20 and P80 in the table) are indicated in PE and GHG figures to address the sensitivity of the results. For PE use, P20 and P80 were calculated based on the P20 and P80 of total energy expended (renewable and non-renewable) given by Edwards et al. (2014c), assuming the share of renewable energy use to be the same for P20 and P80 as for the median value. For electricity, data were based on (Gode et al., 2011), assuming Nordic electricity mix.

Crop cultivation for biofuel production is often associated with direct or indirect land use change (European Commission, 2015; Valin et al., 2015). In the report used as data source for this study, land use change is considered important but difficult to estimate quantitatively as it occurs over a long period of time, and is therefore not included (Edwards et al., 2014b).

Table 1 – Fuel properties used in calculations. <sup>a</sup>Data from (Emissionsberäkningar i FRIDA, 2017); <sup>b</sup>Data from (Edwards et al., 2014c); <sup>c</sup>Data from (Westin and Forsberg, 2015); <sup>d</sup>Nordic electricity mix, from (Gode et al., 2011).

Fuels and energy sources	JRC pathway code <sup>b</sup>	Energy content in fuel <sup>a</sup>		Non-renew. PE use <sup>b</sup> , kWh <sub>PE</sub> /kWh fuel			Non-renew. GHG emissions, g CO <sub>2</sub> -eqv/kWh fuel <sup>b</sup>								Energy sources <sup>c</sup> % of fuel			
		kWh/l	kWh/Nm <sup>3</sup>	Fraction renewable energy input	Total non-renewable PE use	Range P20 P80	Production and conditioning at source	Transformation at source	Transportation to market	Transformation near market	Conditioning and distribution	Combustion	Total WTW	Range P20 P80				
Biogas		-	13.0		0.29	0.26	0.32											
- Municipal waste	OWCG1			67%	0.33	0.27	0.37					41.4	11.9	0	53.3	40.7	65.2	60%
- Manure	OWCG21			88%	0.24	0.23	0.24	-296.6	5.0		28.4	11.9	0	-251.3	-256.7	-247.7		40%
Ethanol		5.8	-		0.77	0.76	0.77								229.4	217.0	237.9	
- Wheat	WTET2a			53%	0.77	0.76	0.77	181.8		3.6	42.1	5.8	0	233.3	221.0	240.8		64%
- Maize	CRET2a			41%	1.02	1.02	1.03	208.4		3.2	71.6	5.8	0	289.1	275.8	299.9		20%
- Barley	SBET1b			69%	0.39	0.35	0.42	65.2		13.7	13.0	5.8	0	97.6	87.8	104.0		8%
- Sugar beet	BRET2a			55%	0.82	0.81	0.82	229.3		4.0	34.2	5.8	0	273.2	253.1	289.8		4%
- Sugar cane	SCET1			92%	0.16	0.16	0.16	64.4	-5.0	24.1		5.8	0	89.3	81.7	96.8		4%
FAME		9.3	-		0.48	0.48	0.49								205.6	181.4	231.5	
- Rapeseed	ROFA3			57%	0.48	0.48	0.49	207.4		2.2	-9.0	5.0	0	205.6	181.4	231.5		100%
HVO		9.5	-		0.2	0.19	0.21								64.1	79.0	81.9	
- Waste cooking oil	WOHY1a			16%	0.14	0.13	0.14				24.5	4.7	0	29.2	46.8	50.0		63%
- Tallow oil	TOHY1a			7%	0.41	0.41	0.41	0.7	62.3	1.4	19.1	4.7	0	88.2	106.9	108.0		22%
- Palm oil	POY1a			85%	0.17	0.17	0.17	97.2	39.6	15.5	18.4	4.7	0	175.3	173.2	177.1		15%
Electricity <sup>d</sup>		-	-	67%	1.74									97.3				
Diesel	COD1	9.8	-	1%	1.2	1.18	1.23	16.9		3.6	31.0	4.0	263.5	319.0	313.2	324.7		
Natural gas	GMCG1	-	13.0	5%	1.16	1.13	1.18	14.4		18.4		14.0	202.7	249.5	245.2	254.2		

In the FRIDA database, energy use in bus transport is most often only reported per propulsion system and per vehicle-km. As diesel engines can run on either fossil diesel, HVO or FAME and gas engines can use either natural gas or biogas, this makes it difficult to accurately determine the energy use per fuel. As an estimate, the energy use per fuel was assumed to be proportional to the vehicle-km per fuel for the respective propulsion system. For example, if HVO was used on 70% of the vehicle-km where diesel engines were used, then 70% of the energy used in diesel engines was assumed to be in form of HVO.

In order to try to explain variations in the energy use in buses between different regions, six parameters were selected and checked for correlation with the fuel use: propulsion system; share of renewable fuels; transport volume; share of population in urban areas; age of buses; and share of buses that comply with Euro 5 or Euro 6 standards. The first parameter was defined as “share of buses with diesel engines”, as diesel engines are known to be more energy efficient compared to other types of engines used in buses (Xylia and Silveira, 2017). The share of renewable fuels was taken as the share of the total number of vehicle-kilometres operated with renewable fuels. The share of population in urban areas was defined as the “share of the population that live in cities with more than 10 000 residents”. This parameter is intended as a proxy for the share of city buses, as the transport operators report no data on this. Finally, the age of buses and the share of buses that comply with Euro 5 or 6 were chosen to investigate if newer buses with better engines are more fuel efficient than older buses. Data on propulsion systems, transport volume, age of buses and their compliance with the Euro standard were collected from FRIDA (Nordic Port, 2017), while population statistics were retrieved from SCB Statistics Sweden (SCB, 2016a, 2016b). The correlation between two parameters was calculated according to:

$$\text{corr}(X, Y) = \frac{\text{cov}(X, Y)}{\sigma_X \sigma_Y} \quad (1)$$

where  $\text{corr}(X, Y)$  is the correlation coefficient of the two parameters  $X$  and  $Y$ ,  $\text{cov}(X, Y)$  is the covariance of  $X$  and  $Y$ , and  $\sigma_X$  and  $\sigma_Y$  are the standard deviations of  $X$  and  $Y$ , respectively (Dowdy and Wearden, 1983). The correlation coefficient can take values between -1 and 1, where a value close to -1 or 1 indicates a strong negative or positive correlation, respectively, and  $\text{corr}(X, Y) = 0$  means that there is no correlation between  $X$  and  $Y$ .

Data in (Rhudin et al., 2017) as well as in this paper are presented with a regional division, referring to the 21 administrative regions of Sweden (Figure 1). In addition, aggregated data for the whole country is included for comparison.

Figure 3 shows the average number of people travelling with the buses in the Swedish regions in 2016 (Wiklund and Greijer, 2017). Dalarna stands out with the highest number of passengers per bus, while Gotland has the lowest. According to Rhudin et al. (2017), the high number of bus travellers in Dalarna, a rather sparsely populated region, has to do with the long average distance of the bus routes. It should be noted that the three most populated regions – Stockholm, Västra Götaland and Skåne – account for over 80% of the journeys in public transport in Sweden (Wiklund and Greijer, 2017) and have great impact on the national average. The number of passengers per bus is used in this paper to convert vehicle-kilometres to passenger-kilometres, which is the product of vehicle-kilometres and number of passengers.

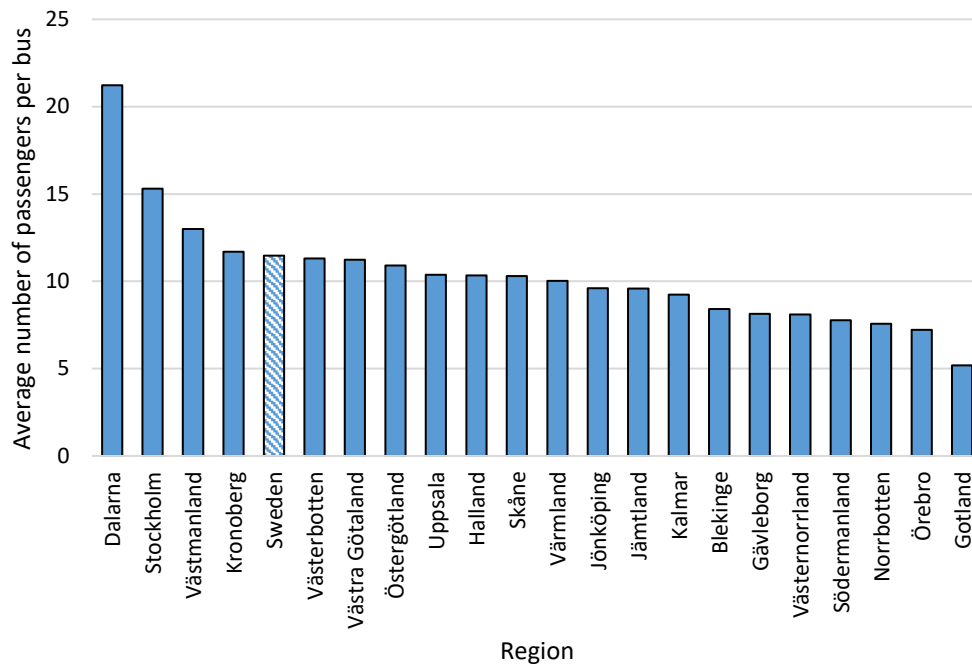


Figure 3 – Average number of passengers per bus in the Swedish regions, 2016 (Wiklund and Greijer, 2017)

## 4. Results and Analysis

In this section, different ways of assessing the energy performance of public bus transport are presented and analysed, both regarding use of fossil and renewable fuels and energy efficiency. In addition, correlations between the energy use in buses and other regional differences related to the public bus transport system are presented and analysed.

### 4.1. Use of fossil and renewable fuels

In 2016, 77% of the public bus transport work in Sweden was performed with renewable fuels (Figure 4). The most important renewable fuels were FAME (29%), HVO (23%) and biogas (21%). Both the total share of renewable fuels and the specific fuel mix differed largely between the regions. While more than 95% of the bus transports in Västmanland, Stockholm and Blekinge were based on renewable fuels, 94% of the bus transports in Gotland used fossil diesel. Västmanland, Skåne and Östergötland had the highest share of biogas in their respective fuel mixes. FAME dominated in Västra Götaland, Södermanland, Stockholm, Kronoberg and Halland, while HVO was the most common in Västernorrland, Gävleborg, Dalarna and Blekinge.

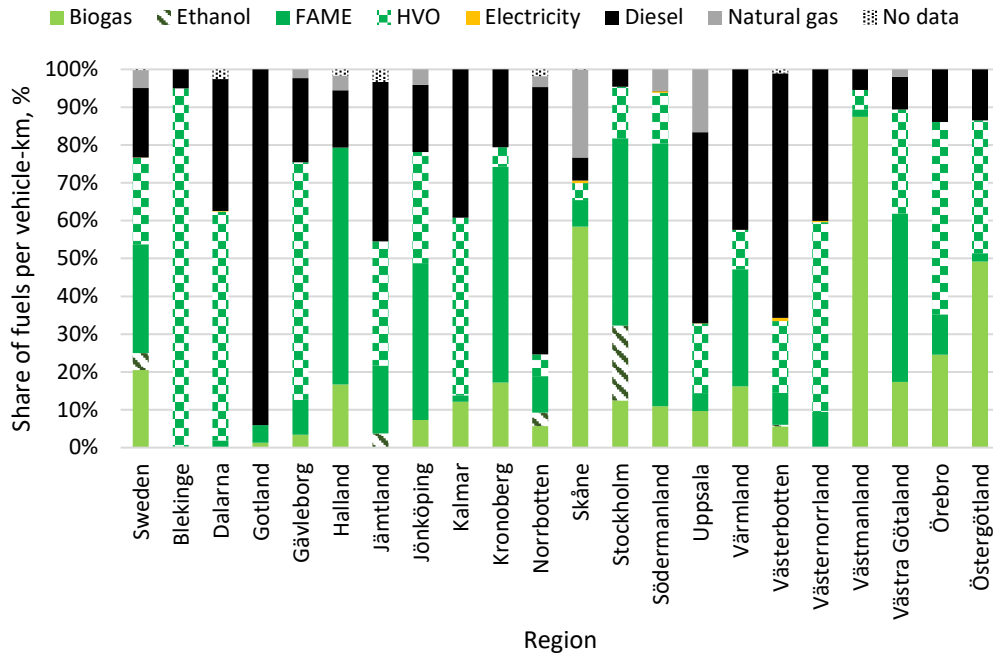


Figure 4 – Share of fuel per vehicle-km on a regional and a national level

Figure 5 shows the relative reduction of fossil energy use in different regions with the bus transports structure in 2016 compared to a scenario with 100% fossil diesel. This analysis, which is based on the JRC well-to-tank report (Edwards et al., 2014c), takes into account the fossil energy use over the whole life cycle of the fuels, including production and distribution. Thus, this indicator reflects the difference between HVO, FAME, ethanol and biogas. Likewise, the indicator “Relative reduction of GHG emissions” takes into account all emissions of greenhouse gases during the fuel life cycle. The regions using a large share of biogas in their bus fleet – Skåne, Östergötland and Västmanland – have a larger reduction of GHG emissions, because of the GHG capture in biogas production from manure (see Table 1). Applying the 20<sup>th</sup> or 80<sup>th</sup> percentile GHG emission factors gives an error margin within  $\pm 11\%$  of the median values, with an average for all the regions of  $\pm 5\%$ .

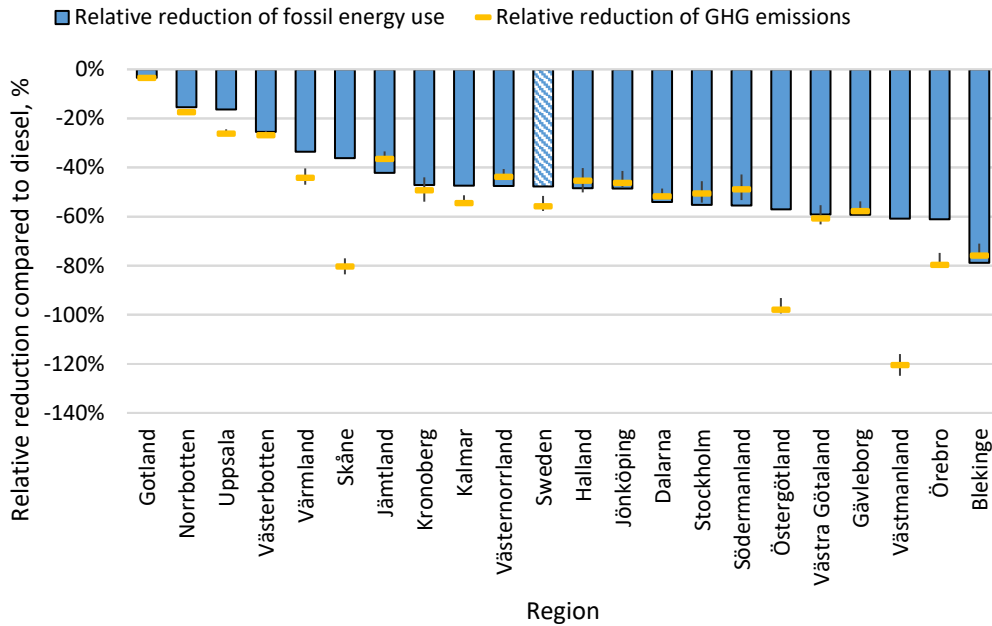


Figure 5 – Relative reduction of fossil energy use and GHG emissions (well-to-wheel) in bus transport, compared to a scenario with 100% fossil diesel use

Compared to the shares of renewable fuels presented in Figure 2, the analysis presented in Figure 4 provides more information about which fuels that are used and how they affect the environmental performance of the regional bus transport systems. In order to achieve both a high share of renewable fuels and a large reduction of GHG emissions, it is both important to consider which renewable fuels that are used and their environmental performance in terms of GHG emissions and renewability.

#### 4.2. Energy efficiency

Figure 6 shows four different ways of defining, measuring and comparing the energy efficiency of public bus transport systems. In the upper left quadrant, the fuel use (kWh) per vehicle-km in 2016 in the bus transport systems in Sweden are shown. This is identical to the left half of Figure 2. The data behind the figure refers to the energy use in the buses, i.e. tank-to-wheel. The buses in Dalarna, Gotland, Jämtland, Kronoberg and Västernorrland have, according to this analysis, the most efficient engines, while the least efficient bus engines are found in Västmanland, Skåne, Stockholm, Östergötland and Örebro.

In the lower left quadrant, the well-to-wheel non-renewable primary energy use in different Swedish regions is shown. The most significant differences between this and the previous figure are for the regions of Västmanland and Gotland. Västmanland has moved from the least energy efficient (tank-to-wheel) to the most energy efficient (well-to-wheel), and Gotland has moved in the opposite direction. The error margins shown in the figure are small in relation to the total PE use per region, indicating that using PE factors within the 20<sup>th</sup> and 80<sup>th</sup> percentiles would not alter the order of the regions much.

The chart in the upper right quadrant shows the fuel use in buses in relation to the number of passenger-km instead of vehicle-km. This indicator is in line with the set environmental goals for the transport associations which, however, refer to all types of public transport (*Branschgemensamt miljöprogram 2.0*, 2013). Dalarna stands out as by far the most energy efficient bus transport region. On the other end, Örebro, Gotland, Södermanland and Norrbotten are regions with relatively few

passengers per bus, resulting in higher fuel use per passenger-km. Regions with large population get a higher ranking with this indicator compared to energy use per vehicle-km, while regions with smaller population drop in the ranking.

Finally, the chart in the lower right quadrant shows the non-renewable primary energy use (well-to-wheel) per passenger-km. This indicator takes into account both the energy used for production and distribution of fuels and the performance of the bus transport system in terms of transporting people. Again, Dalarna is in the top due to the high number of passengers per bus. Other regions above the national average have a large share of renewable fuels in their respective mixes: either biogas (Västmanland and Östergötland), FAME (Stockholm and Kronoberg), HVO (Blekinge) or all three (Västra Götaland). Gotland, on the other hand, has the lowest number of people per bus and the largest share of fossil fuels, and ends up with the highest primary energy use per passenger-km. Just as in the lower left figure, the error margins are quite narrow, suggesting that the results are robust.

All four of these charts have relevance as policy support: the left-hand charts steer the choice of buses in procurement while the right-hand charts reflect the efficiency in planning the bus routes and transporting people; the upper charts indicate fuel economy and local emissions while the lower charts concern the life cycle energy use.

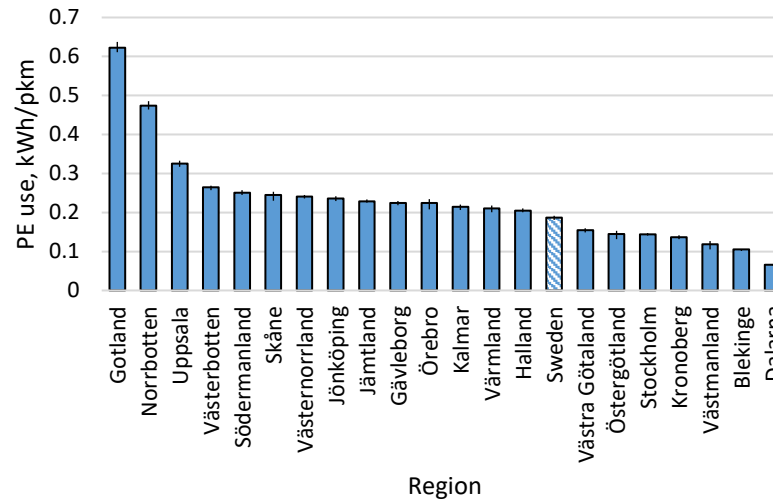
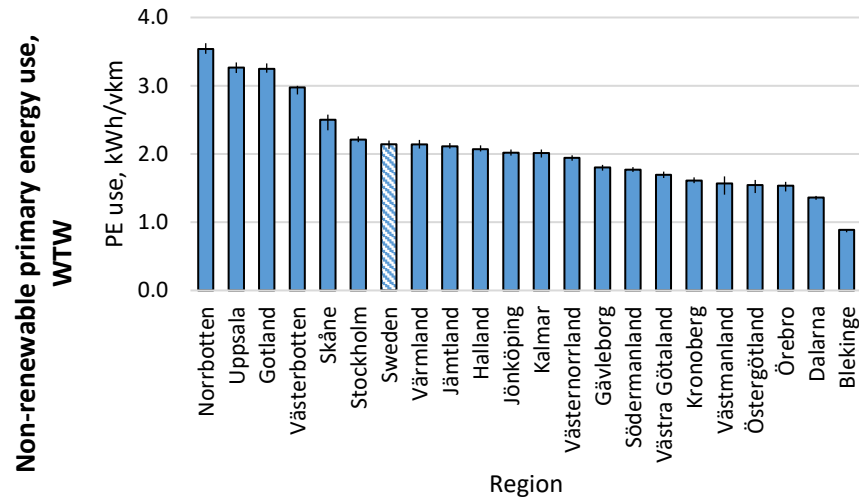
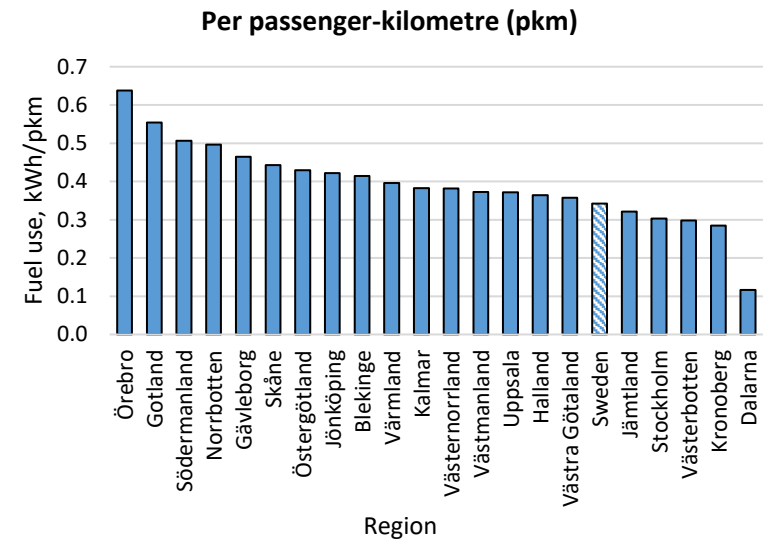
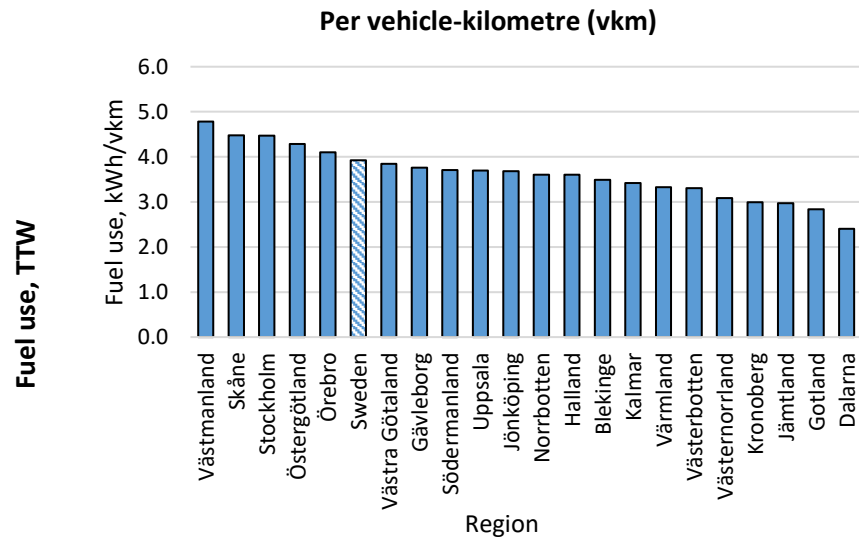


Figure 6 – Energy efficiency of regional bus transport systems in Sweden, based on four different definitions: fuel use per vehicle-km (upper left); non-renewable primary energy use per vehicle-km (lower left); fuel use per passenger-km (upper right); and non-renewable primary energy use per passenger-km (lower right).

### 4.3. Factors affecting the energy efficiency in buses

Figure 7 shows the dependency of tank-to-wheel energy efficiency of: propulsion system (upper left); transport volume (upper right); share of population in cities with more than 10 000 inhabitants (middle left); population density per m<sup>2</sup> (middle right); age of buses (lower left); and share of buses compliant with Euro 5 or Euro 6 standards (lower right). Each point in the charts represent one of the 21 Swedish regions. The national average is not included as a separate point. As already shown in the left half of Figure 2 and the upper left quadrant of Figure 6, the fuel use in the different regions varies between 2.4 and 4.8 kWh/vkm.

The strongest correlation, -0.84, is that between the fuel use and the share of diesel engines in buses (upper left). Calculations of fuel economy show that in 2016 diesel buses in Swedish public transport used on average 3.41 kWh/km, while ethanol buses used 4.23 kWh/km (+24% compared to diesel buses) and gas buses 5.31 kWh/km (+56% compared to diesel buses). The fuels used in diesel buses include fossil diesel, HVO and FAME, while gas buses run on either natural gas or biogas and ethanol buses on ethanol.

The share of vehicle-km operated with renewable fuels (upper right) has a weaker correlation with the fuel use, 0.56, and the trend is that regions with a higher share of renewable fuels have a higher fuel consumption in their buses. This reflects back to the correlation between fuel use and propulsion system, as both gas buses and ethanol buses have a higher energy use than diesel buses. For the regions where none or a small share of biogas and ethanol is used in public bus transport (Blekinge, Dalarna, Gotland, Gävleborg, Jämtland, Norrbotten, Västerbotten and Västernorrland), the correlation is only slightly stronger, 0.59, which suggests no distinct effect on fuel economy of replacing diesel with HVO and FAME.

The correlation between the fuel use and the share of citizens in the regions living in cities with more than 10 000 inhabitants is 0.74 (middle left). Although this correlation is not as strong as the one between fuel use and share of diesel engines, it still indicates a trend towards higher energy use in buses in denser regions. Stockholm is detached from the other regions in the figure, with 90% of the population in cities with more than 10 000 inhabitants. If Stockholm is excluded, the correlation is slightly stronger, 0.76.

The middle right chart shows a weak correlation, 0.48, between the fuel use and the transport volume. There is no clear trend that regions with larger transport volumes use more energy per vehicle-km. In fact, one of the regions with the highest levels of energy use is among the smaller in transport volume (dot to the lower right in the chart).

As for the fuel use and the average age of the buses (lower left), there appears to be no correlation at all, -0.02. With average ages of no more than eight years, most buses in Sweden are new enough to comply with modern engine performance standards. This leads on to the lower right chart, which shows the relation between the fuel use and the share of buses that comply with Euro 5 or 6. The correlation is very weak also in this case, -0.19. In 2016, 88% of the buses in the Swedish public transport sector fulfilled the requirements for Euro 5 or 6, and the differences between the regions are not large enough to explain the variations in fuel use.

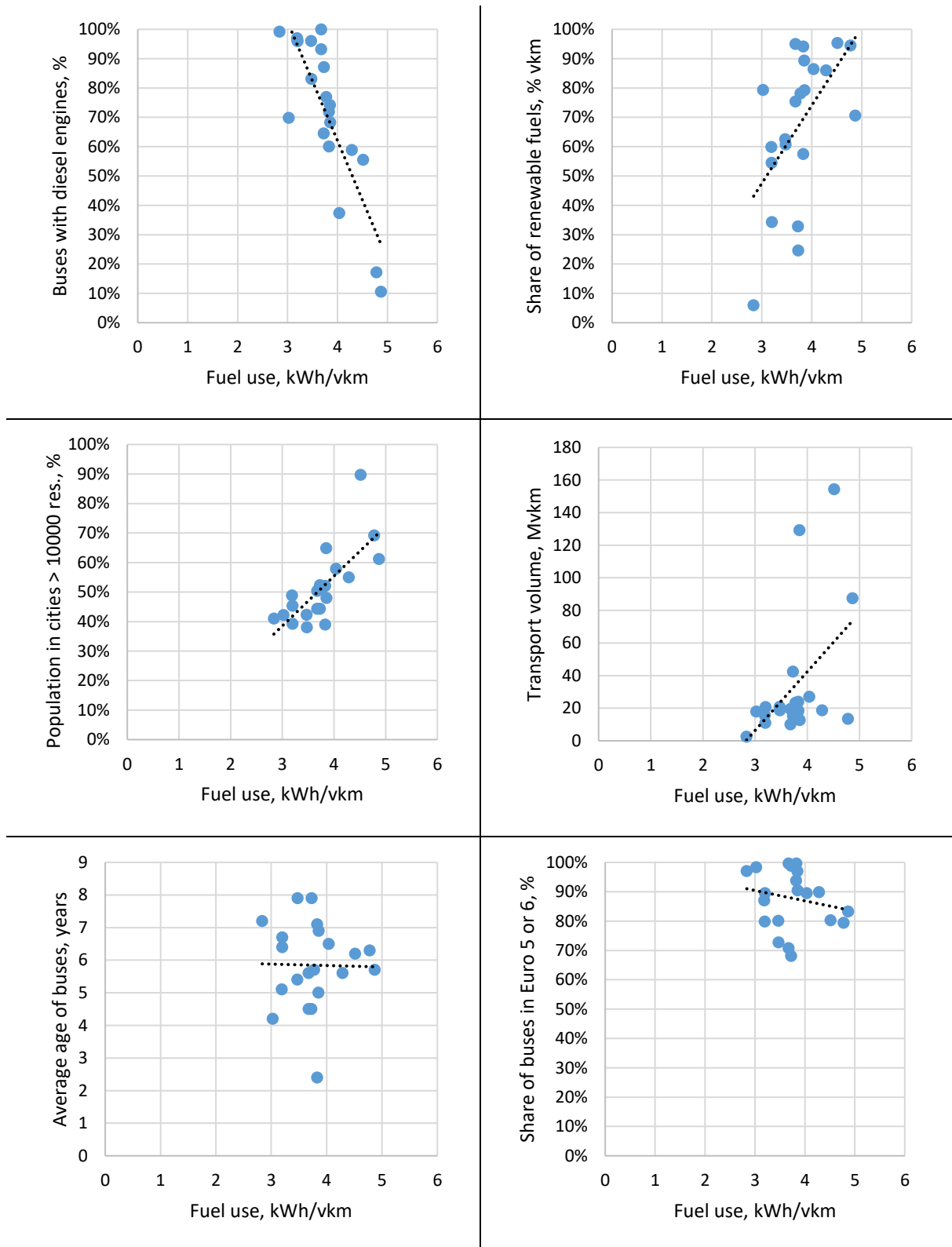


Figure 7 – Energy use per vehicle-kilometre (tank-to-wheel) in relation to the share of diesel engines (upper left), the share of renewable fuels used (upper right), the share of the population that live in cities with more than 10 000 citizens (middle left), the transport volume (middle right), the average age of the buses (lower left) and the share of buses that comply with Euro 5 or Euro 6 standards (lower right). The dotted lines indicate the correlation between the different parameters and the specific energy use of the buses.

## 5. Discussion

Policies intended to aid the work towards energy and climate goals should be supported by relevant data and performance indicators. Considering the European Union goals of reduced GHG emissions and improved energy efficiency (European Commission, 2014), it is not sufficient for the transport sector to address the fuel efficiency of vehicles and the share of renewable and fossil fuels. Many studies today use a life cycle perspective on fuel use to include all the related emissions and energy uses (Börjesson et al., 2010; Lajunen and Lipman, 2016; Nylund and Koponen, 2012; Ou et al., 2010; Xu et al., 2015; Yazdanie et al., 2016). As shown in the present paper, the varying GHG emissions as well as life cycle energy use between different fuels can greatly affect the environmental performance of a transport system. Although the results presented are specific for the Swedish public transport system, the life cycle perspective applied is undeniably important for good data analysis and policy support. Adding more detail to the analysis of transport systems, even though it increases the uncertainty, could definitely help designing adequate policies to achieve the energy and climate goals. For example, information about the types of fuel and their origin is necessary if the goal is to promote biofuels from domestic production and reduce the import dependency.

In the case of Sweden, one critical point in the analysis of public transport is the data collection and reporting. Currently, some regions report energy use to the FRIDA database based on standardised models rather than actual fuel use, and there is no information available on the type and amount of fuel used for individual vehicles or routes (Nordic Port, 2017). There are also uncertainties in the reporting of passenger-km. While it is easy to count the number of people boarding a bus, given that all passengers buy a ticket or register a traveling pass, there is usually no system for registering when passengers get off the bus. The number of passenger-km will then often be based on the distance covered by the bus, rather than the distance travelled by each passenger. This uncertainty is a problem for the assessment of the environmental goals for public transport in Sweden, which are expressed in passenger-km (*Branschgemensamt miljöprogram 2.0*, 2013). Comparisons between different modes of transport can also be considered more meaningful if based on passenger-km (Moriarty and Honnery, 2012).

When analysing a transport system, it is important to consider the variations in energy efficiency between different engine technologies. As shown in Figure 7, the energy efficiency in buses in Sweden is strongly correlated to the share of diesel engines in the regional bus fleets. The fuel use in gas driven buses was found to be 56% higher than in diesel driven buses. This number, however, is considerably higher than the 36% noted by Xylia and Silveira (2017) and, likewise, by Zhang et al. (2014), or the 25% reported by Lajunen and Lipman (2016). The difference between diesel and gas found in the present paper could be enhanced by a higher use of alternative engine technologies in city traffic, where buses on average use more fuel due to frequent starts and stops (de Abreu e Silva et al., 2015; Rhudin et al., 2017). It should also be noted that the share of renewable fuel use, as shown in Figure 4, should be expressed in relation to the transport distance rather than the amount of energy used of each fuel. The same approach is used in the report from SKL (analogous to Figure 2, right). By doing so, the differences in energy efficiency between different propulsion systems is excluded. Specifically, biogas would count more per kWh fuel than per vehicle-km, as gas engines are less efficient and use more fuel per km than diesel engines.

In a life cycle (well-to-wheel) perspective, none of the fuels used for public bus transport are entirely fossil-free, as indicated by the non-renewable primary energy factors in Table 1. This becomes clear when comparing Figure 4 and Figure 5: despite using more than 95% renewable fuels in public bus transport, the regions of Blekinge, Västmanland and Stockholm only reduce the fossil energy use compared to fossil diesel by 79%, 61% and 55%, respectively. Regarding GHG emissions, there is a

perhaps even clearer difference between the renewable fuels, as the regions that use a lot of biogas reduce the GHG emissions more in relation to the reduction of fossil energy use compared to other regions. This is due to the fact that production and combustion of biogas from manure captures methane that would otherwise be released to the atmosphere and converts it to carbon dioxide, which is a significantly less potent GHG.

The life cycle impact of fuels is not limited to energy use and greenhouse gas emissions. A broader analysis could also include other types of environmental impact as well as economic and social sustainability. The possible effects of crop based biofuel production on food production and food prices are frequently debated (Ben Fradj et al., 2016; Pimentel and Burgess, 2014; Popp et al., 2014; Tomei and Helliwell, 2016; Wiggins et al., 2008). For the biofuel pathways used in this study, this could affect the economic and social aspects of ethanol, FAME and palm oil based HVO, whereas other pathways for HVO and biogas are based on organic waste rather than dedicated energy crops.

There are clearly large differences between the Swedish regions when it comes to their conditions for public transport, including population density and division between rural and urban areas, the transport habits and needs of the inhabitants, as well as existing infrastructure and modes of transport. Some regions, like Dalarna, are more dependent on bus transport due to limited railroad network (Rhudin et al., 2017), whereas some cities have tram lines (Gothenburg, Norrköping) or subways (Stockholm) as alternatives to the buses. When comparing energy efficiency and fuel use, it is important to bear this in mind, to try to see through the numbers and understand why there are such large differences.

## 6. Conclusions

In this paper, different ways of assessing and presenting the energy performance of public bus transport systems have been investigated. The analysis included use of renewable and fossil fuels as well as energy efficiency and its underlying factors, with the aim to demonstrate different possible indicators and discuss their applicability for policy support.

In the assessment of the use of renewable fuels in public bus transport, there are clear advantages of increasing the level of detail from renewable and fossil fuels to specific fuels. Different renewable fuels carry different loads of energy use from production, resulting in more or less severe impact on the environment. These aspects are important to consider when choosing fuels that are beneficial in the work towards reaching environmental goals such as reduced GHG emissions.

Likewise, the picture of energy efficiency in buses becomes more complete with a well-to-wheel perspective, taking into account the energy use over the whole life cycle of the fuel. Efficient engines are also important, but the total energy efficiency is dependent of the fuel that is used. Whether the energy use is set in relation to the amount of vehicle-km or the amount of passenger-km is mainly of interest for the transport operator. Densely populated regions will naturally have a relatively high number of passengers per bus and a more efficient transport system in terms of ability to transport people compared to sparsely populated regions.

Regional differences when it comes to energy efficiency in buses can to a large extent be explained by the use of different propulsion systems. Higher fuel consumption in city traffic compared to routes outside the city could also influence the overall efficiency, but is secondary to the discrepancy in efficiency of diesel engines and gas engines.

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