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Biofuels in the energy transition beyond peak oil. A macroscopic study of energy demand in the Stockholm transport system 2030

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Abstract

The objective of this study is to examine the potential for a full transition to domestically produced biofuels in the Stockholm County transport system in 2030, without exceeding the proportional share of national bioenergy assets. This target is chosen in order to test the potential of biofuel assets in Sweden, facilitating the transition to renewable fuel systems, and to display the potential of transport energy demand at macrolevel under tighter conditions on the energy market after fossil oil production has peaked. The distribution of bioenergy to the transport sector, including conversion losses and relationships to other energy sectors, is analysed explicitly. State-of-the-art traffic forecasting models, complemented with a specially designed energy quantification model, are applied to assess energy quantities needed at different vehicle efficiency levels and mobility patterns. The purpose is not to determine the most energy-efficient transport system possible, or to forecast the optimal distribution of bioenergy set aside for the transport sector in the future. Rather, we try to visualise, at a more conceptual level, energy demand as dependent on principle transport strategies, future technological developments and a type of planning that takes technological interlinkages between evolving components into strategic account. This work highlights the importance of implementing both demand and supply-side policies in order to reduce energy use and greenhouse gas emissions in all energy sectors before making assessments of reasonable distributions of bioenergy between energy sectors and other biomass usage.

Keywords: Sustainable transport; Renewable energy; Energy efficiency; Transport policy; Strategic planning; Backcasting

1. Introduction

Global production of oil and gas is approaching its maximum (*peak oil*) and the world is now finding one new barrel of oil for every four it consumes [1]. Consequently, a need for energy efficiencies and feasible strategies for transition to renewable fuels will strike all energy sectors in the near future.

Transport accounts for 31% of energy use in the EU [2]. Because of the rapid growth and dominant use of fossil fuels, transport is often characterised as the most unmanageable energy sector [3], difficult to include in emission trading programmes [4]. In particular, emissions from road traffic account for about 23% of total CO_2-equivalents in the EU and are expected to increase [5]. The Swedish government has declared a goal of phasing out fossil fuels in the transport sector by 2020. The recent report of the government-appointed fact-finding commission on petroleum dependency predicts that this goal, which amounts to a 50% reduction in total petroleum use in Sweden, can be reached in the appointed year [6]. The remaining 50% is planned to be phased out successively thereafter.

To handle the complexity of the coming energy transition, strategic, target-orientated planning is needed. In this study we apply a backcasting framework [7] where the target for the transport system in 2030 is based on a local balance between energy demand and renewable energy supply. The aim is to display the potential of biofuels in relation to requirements on energy efficiency

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following the expected decline in global production of oil in the near future after peak oil. At a local level, keeping track of the balance between energy demand and renewable energy supply is a valuable objective in order to avoid a skewed distribution of resources between nations and regions over the world. An extensive analysis carried out in Lower Fraser Valley, Canada, highlighted the inevitable need for more energy-efficient urban mobility and vehicle technologies if local renewable energy assets are not to be exceeded [8].

The potential for biomass worldwide is, generally speaking, large [9,10]. As we approach peak oil, we may expect the development of species of crops and trees that are especially well-suited for fuel production and adapted to different regions and climatic conditions. For instance, methanol is interesting as an energy medium and as a medium for the distribution of hydrogen, since there are a number of chemical–physical mechanisms that facilitate conversion to and from methanol. Methanol is also convenient to use as a fuel itself [11]. There are a number of competing biofuel production processes that need further investigation as regards cost effectiveness, utilisation, resources availability, etc. [12,13].

Furthermore, in order to reduce the cost-effectiveness gap in biofuel production within the EU in relation to imports from other regions of the world (e.g. Brazil), it is essential to reach production volumes that would improve economies of scale and engender innovation as regards production processes [14]. In order for this to happen, biofuel production is dependent on subsidies and tax-exemptions in the starting phase. One way to stimulate domestic bioenergy production within the EU is through the Common Agricultural Policy (CAP), creating a single market for agricultural products, with free exchange and lower prices of goods between member countries [15]. According to Ryan [16], the three strongest motives for subsidising biofuel production within the EU, although not necessarily cost-effective at present, are to: (a) avoid exceeding target for greenhouse gas emissions set by the Kyoto Protocol, (b) reduce dependence on oil imports from the Middle East, and (c) create job opportunities in declining rural areas. Yet another motive would be to mitigate depletion of biofuel resources in developing parts of the world, which in the long run could harm economic growth, biodiversity and food supply in these regions [17,18].

Future competition for energy resources and the concomitant increase in energy prices will probably steer future car use and car production in a more energy-efficient direction [19,20]. In many cities in the industrialised parts of the world, more cost- and energy-efficient urban mobility is encouraged through subsidised company travel plans and specific mobility management initiatives targeting less car-dependent personal travel [21].

This study may contribute to discussions on a number of decisive factors relating to use of biomass for energy production. These include deciding a realistic proportion of biofuels to set aside for the transport sector in relation to other usage of biomass (other energy sectors, food production, forest and paper industries, etc.), and determining the extent to which other renewable energy systems might contribute to energy demand [10,22–24]. With respect to this complexity, our intention is to keep the number of degrees of freedom to a minimum, in order to display potential energy assets set aside for the transport sector, in relation to our backcasting target.

In the following section we present an empirical example of how three system components (domestic energy supply, fuel and vehicle technology, efficient mobility), put into operation in the Stockholm transport system, could meet the target of a full transition to biofuels.

2. Three system components

In this study we examine the following principle target: *A full transition to domestically produced biofuels in the transport system of Stockholm County in* 2030, *without exceeding the proportional share of national bioenergy assets*. This target was chosen in order to: (a) test the potential of biofuel assets in Sweden, facilitating the transition to renewable fuel systems and (b) to display the potential of energy efficiencies in the transport system to meet with future more restrictive conditions on energy efficiency after the peak of fossil oil production. The backcasting target and the feasible backcasting paths are modelled and quantified in Section 3. The use of bioenergy to the transport sector in relation to other energy sectors is analysed explicitly.

Placing ourselves in this desired vision, we look back, asking the question: What is needed to achieve this? This goal-orientated backcasting approach, identifying obstacles and seeking answers on how to overcome them, is well applied on any level of sustainable transport research (e.g. at company level [25], regional level [26] and national or international level [27,28]). Robèrt [29] and Ny [30] advocate principle targets (principles for sustainability) rather than fixed images of the future. This allows greater flexibility in long-term planning, and a more dynamic and adaptive evolutionary process. This is because the future holds many possible investment paths towards compliance with principle targets, and it may not be desirable to choose prematurely between those. It is often easier (and smarter) to agree on early investments that are flexible with regard to principle targets, and re-evaluate as the process unfolds and technical evolution keeps changing the conditions, than to agree on specific distant futures. Robèrt and Jonsson [26] utilise mathematical forecast models as a tool for guidance in the backcasting framework when evaluating effective paths to future emission targets in Stockholm.

We assume there are three crucial mechanisms for making both ends meet in the vision of a non-fossil fuel transport system for the Stockholm region: (a) the potential for domestic production of biofuel without exceeding the capacity of Swedish agriculture and forests, where resources other than fuels must also be harvested; (b) the energy efficiency potential of future vehicles; and (c) the energy efficiency potential of urban mobility. The interrelationships between these three system components are illustrated in Fig. 1. These three mechanisms (a–c) form a countless number of possible combinations fulfilling the requirements of the principle target, i.e. feasible backcasting paths. We use traffic forecasting models to generate a few examples in which we assess energy quantities needed at different vehicle efficiency levels and mobility patterns in Stockholm 2030. The purpose is not to determine the most energy-efficient transport system possible, or to forecast the optimal distribution of bioenergy set aside for the transport sector in the future. Rather, we try to visualise, at a more conceptual level, energy use as dependent on principle transport strategies, on technological developments for the future, and on a type of planning that takes technological links between the evolving components into strategic account.

2.1. Potential for renewable fuel production in Sweden (A)

2.1.1. Swedish energy use

National energy use in Sweden during 2004—divided into a few different types of use—is summarised in Table 1 [31]. Energy quantities are given in kilowatt-hours throughout this study (1.0 kilowatt-hour (kW h) = 3.6 MJ).

Total energy use in 2004 amounted to 624 TW h/yr and national transport accounted for 96 TW h/yr (Table 1). Energy use from road transport accounts for about 70% of total energy use in the transport sector [32]. The energy needed for the transport sector is the part of national energy consumption that is most difficult to replace by alternative sources and technologies, and perhaps the part needing the greatest attention in the context of post peak oil [6].

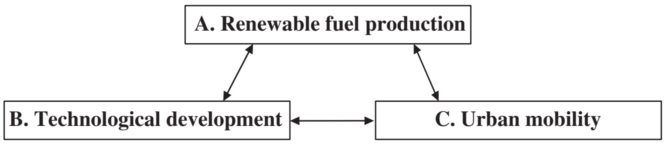

Fig. 1. The three system components of a renewable urban transport system explored in this study. The interrelationships between all components influence the prospects of a renewable transport system.

Table 1
Swedish energy use in 2004, divided into different types of use [31] (1.0 kilowatt-hour (kW h) = 3.6 MJ)

Type of use	TW h/yr	%
Residential, services, etc.	157	25.2
Industry	154	24.7
National transport	96	15.4
Conversion and distribution losses	177	28.4
Foreign maritime trade and other use	40	6.4
Total energy use	624	100.0

2.1.2. Swedish biomass energy potential

The amount of biomass energy that can be made available until 2030 is not easy to assess with certainty. However, with respect to biomass, Sweden is a favoured country in Europe and in the world.

Table 2 shows Swedish land use in the year 2000 according to Statistics Sweden 2006 [33]. More than 50% of Sweden's land area is covered with forests. Another measure of the Swedish forest resources is that with 9 million inhabitants in Sweden, each person has more than 2.5 h of forest land. This is a high share in an international comparison, considering Germany with approx. 0.15, Denmark with 0.09 and Poland with 0.23 h per capita [34]. In other words, Sweden has 10–30 times more forest biomass per person than other neighbouring countries with a similar climate and thus has a higher potential for biomass energy supply.

The total agricultural land area in Sweden is approximately 35 000 km^2 (Table 2). Of this land, a considerable proportion is gradually being taken out of agricultural production and either converted to forest land or maintained as agricultural land without production (landscape maintenance). Approximately 30% could be redirected to other types of production, such as biomass energy [35].

Table 3 gives a calculation example with simplified numbers, based on a few key assumptions, such as for the forest:

- 20% of the national forest area will be nature reserve in the long term;
- 5% will be managed for natural conservation or for urban recreation purposes with a low potential for biomass production;
- 50% will be managed in a rather traditional way, most of the biomass being diverted to timber and pulp and paper production, as previously;
- 15% will be managed in a more innovative way with e.g. plantations of rapidly growing tree species and with forced fertilisation;
- 10% will be used for cultivation of special biomass energy crops such as poplar or willow and used exclusively for biomass energy.

Table 2
Swedish use of national land in the year 2000 [33]

Type of land	km^2	%
Forest land	235 065	52.2
Agricultural land	34 666	7.7
Built-up land	12 877	2.9
Golf courses and ski slopes	304	0.1
Pits	473	0.1
Open marsh land (excl. pits)	38 680	8.6
Natural grassland	32 300	7.2
Bare rock and other land	55 975	12.4
Water (lakes, rivers)	39 960	8.9
Total land	450 300	100.0

Table 3
An example of the Swedish potential for biomass energy

Forest land use	Area (%)	Area (km^2)	Wood (m^3/ha yr)	Biomass (ton DM/ha yr)	Biomass (ton DM/yr)	Oil equiv. (ton/yr)	(TW h/yr)
Nature reserve	20	47 013	3	n.a.		0	
Urban recreation forests	5	11 753	5	1.5	1 762 988	849 633	10
Traditionally managed forests	50	117 533	5	0.3	3 525 975	1 699 265	20
High yielding traditional forests	15	35 260	10	0.6	2 115 585	1 019 559	12
Intense biomass forests	10	23 507	20	6	14 103 900	6 797 060	78
Total forest land		2 35 065			21 508 448	10 365 517	119
Agricultural land							
Food production	70	24 266					
Energy biomass production	30	10 400		10	10 399 800	5 011 952	58
Total agricultural land		34 666			10 399 800	5 011 952	58
Total		198 452			31 908 248	15 377 469	177

Conversions used: 1 kW h = 3.6 MJ; 1 ton TS of biomass = 20 000 MJ; 1 ton of oil = 41 500 MJ. A calculation example of the potential for biomass energy production in Sweden, considering different types of land use and assuming (i) same harvest of wood for timber and pulp and paper as in 2005 and (ii) the use of 70% of total agricultural land for food production and 30% for biomass production.

The total yield of forest biomass is estimated at 5 m^3 of wood per hectare and year as a national average for traditional forestry and 10 and 20 m^3 of forest biomass per hectare and year for high yielding traditional forests and intensely cultivated forests, respectively. In the calculation example, 20 m^3 of forest biomass is assumed to correspond to 6 ton of dry biomass per hectare and year which is a low estimate [36]. In a similar way, 70% of agricultural land is assumed to be used for food production and 30% for cultivation of annual biomass crops with a biomass yield of 10 ton of dry matter per hectare and year. Given these assumptions, Table 3 shows the potential contribution from forest and agricultural biomass in Sweden 2030.[1]

Similar, albeit somewhat lower, figures were obtained in an extensive study by Hagström [37], who found the biomass energy potential in Sweden to be 145 TW h/yr, without including black liquor from the pulp and paper industry. Energy use for cultivation, harvest and processing is not considered in the calculations given in Table 3.

2.1.3. *Well-to-wheel efficiency of biofuel production*

In this section, we estimate the well-to-wheel efficiency of Swedish biomass to transport fuel. We start with forest biomass efficiency and continue with agricultural biomass. In Sweden forest biomass accounts for the main part of the overall biomass potential (almost 70%). The situation is quite different in most other European countries, where the main potential is in the agricultural sector.

When calculating the well-to-wheel efficiency from biomass to biofuels it is important to incorporate the energy conversion losses associated with: (a) the process from crop to the primary processing, including fertilisation, harvesting and transportation to the mill and (b) the industrial process from biomass to various types of biofuels (methanol, ethanol, Fisher–Tropsch diesel, DME, etc.). Comparing the quantity of energy in 1 m^3 of Swedish timber (on average 7700 MJ) to the energy lost at step (a), this energy loss comprises $150-200\,\mathrm{MJ/m^3}$ of timber, depending on the location within Sweden, which would correspond to less than 3% energy loss [36]. Step (b), on the other hand, depends on the type of biofuel conversion process and the level of optimism regarding assumed technological development and the scale of distribution systems in 2030. Assuming that surplus solid waste from the conversion process is used in the heating and electricity sector, current energy loss from wood chips to biofuels (second generation biofuels) comes to about 50–55% for ethanol, about 40–50% for methanol and Fischer–Tropsch fuels, and about 30–40% for gaseous hydrogen [38–40].

In energy biomass production from agricultural land, on the other hand, step (a) accounts for as much as 10–15% energy loss, depending on the type of crops cultivated. In step (b), however, energy loss is already less than 30% for conversion of high yielding crops to biofuels [41].

Net energy yields for biomass production are likely to increase in the future due to advances in plant breeding, technological developments, improved cultivation systems and decreased biomass transportation distances because of benefits from economies of scale [42,43]. In the creation of backcasting paths (Section 3), we assume a fairly modest assumption of on average 40% energy loss in the well-to-wheel process in 2030, including both steps (a) and (b) of the conversion process.

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[1] According to the Swedish Board of Agriculture (Jordbruksverket, March 2007), the total amount of agricultural land in the country is ca. 27 000 km^2 (in 2006) and in addition to this, there are some 5000 km^2 that should be characterised as grazing land. Approx. 3000 km^2 is directly available for alternative production such as agricultural biomass crops (they receive EU support as non-cultivated farmland). According to the Swedish Board of Agriculture, the amount of land cultivated for food production will continue to decrease and in a 10–15 year period it is a valid assumption that 20% of the farmland according to Table 2 (ca. 7000 km^2) could be made available for high yield biomass crops with a yield of 15 ton of dry biomass per year. Given the figures from Swedish Statistics and the Swedish Board of Agriculture, Table 3 shows our assumptions of the potential contribution from forest and agricultural biomass in Sweden in the year 2030.

2.2. Technological development (B)

In this section we present a few alternative technological developments leading to at least 50% fuel efficiency. At a test basis, some breakthrough technologies potentially reduce energy use by up to 70%.

According to Romm [20], there are six major barriers to vehicles run on alternative fuels (e.g. electricity, biofuel, biogas, hydrogen):

1. High first cost for vehicle.
2. On-board fuel storage issues.
3. Safety and liability concerns.
4. High fuel cost (compared to gasoline).
5. Limited fuel stations: chicken and egg problem.
6. Keen competition with better, cleaner gasoline vehicles.

Combustion engines, diesel engines in particular, are becoming more efficient, according to recent well-to-wheel analysis [44]. However, this will only help us to increase energy efficiency by around 20%. Assuming a breakthrough in current research on battery technology, small plug-in vehicles will immediately be a very attractive alternative, in particular for short to medium range commutes. Hybrid technologies are currently being launched as means to bridge the gap between combustion and electrically powered engines and have the potential to cut energy use by up to 50% [20]. One of the most far-reaching technological pathways for the future would be adaptation of electrically driven vehicles that run on rails without a driver, the so-called podcars (also known as personal rapid transit or urban light transport). This would imply a total rearrangement of the transport system but to the benefit of increased energy efficiency by more than 70% in comparison to standard cars [45].

Several studies predict an impending hydrogen economy era, where renewable production of hydrogen for fuel cell vehicles will prevail as the superior technological development for the future [46]. However, from a greenhouse gas perspective, the vast positive effect comes first when hydrogen is produced from renewable energy sources [47]. Fuel cells embedded in hybrid systems, preferably fuelled by on-board reformed hydrogen from glucose/mannitol [48], might produce cars having up to three times higher energy efficiency than today's conventional combustion engines [19,49–51]. Ultra light the so-called hypercars, powered by solar hydrogen, would theoretically reach the same energy efficiency as podcars [52].

There are two obvious advantages coupled to hydrogen-powered fuel cell technology that are important to keep in mind when discussing the energy efficiency rates of alternative vehicle technologies. First, there is a potential synergy effect between the transportation sector and other energy sectors in the society, where e.g. large-scale hydrogen production processes could minimise costs and logistics in the supply chain to the transport sector, as well as to the electricity sector [19]. Second, the storage capacity of hydrogen makes it a flexible energy carrier for different types of renewable energy sources throughout the world. From a global perspective, this multiple source feature of hydrogen is significant, since it makes it possible to convert renewable energy from different geographical regions into the same type of fuel [53,54].

However, fuel cell technology still has to overcome most of the six barriers discussed, in particular the high first cost of vehicles and the availability of scarce metals used in the current technologies [55]. However, because of the increased cost of fossil fuels in the future, fuel cell vehicles will probably be a more cost-effective alternative than conventional cars within 10–15 years [56].

In essence, there are numerous competing technological pathways leading to at least 50% higher fuel efficiency in comparison to present vehicles. Thus, considering that Sweden has one of the most energy-consuming vehicle fleets in the EU and the world [57], a combination of increased energy prices after peak oil, together with various travel demand measures, ought to improve energy efficiency in private vehicles by at least 50% in 20 years.

In the next section we analyse the macroscopic energy demand of integrating the fuel-efficient vehicles referred to in this section (50–70%) into the Stockholm transport system. We also test the cost sensitiveness to increased fuel prices and the impact from various travel demand measures, inducing a shift to e.g. public transport and counteracting potential rebound effects.

2.3. Urban mobility (C)

2.3.1. Macroscopic modelling system of vehicle efficiency and urban mobility

This study tests the prospects for a domestic renewable fuel system that would provide inhabitants of Stockholm with a regionally acceptable proportion of these domestic resources for sustainable mobility. In order to assess the demand for renewable fuels in the year 2030, we apply the transport demand model SAMPERS to the Stockholm transport network, represented in the traffic assignment model EMME/2 [58,59]. The SAMPERS and EMME/2 combination is well suited for energy and efficiency assessments of the regional transport system at macroscopic scale, where negative rebound effects from energy-efficient vehicles are incorporated [26]. The modelling system is in fairly wide use in the Stockholm region, especially the EMME/2 networks, which reduces the risk of errors, and adds to the confidence that the models produce reasonable results. The demand models in SAMPERS incorporate state-of-the-art random utility models for trip generation, destination and mode choice, where trip chaining is also taken into account. EMME/2 is used for assigning transport demand to the road and public transport networks. Energy demand in the total transport network is based on the sum of traffic flows at all links.

In the present study, we develop an effect model (see Appendix) in order to calculate energy demand in the

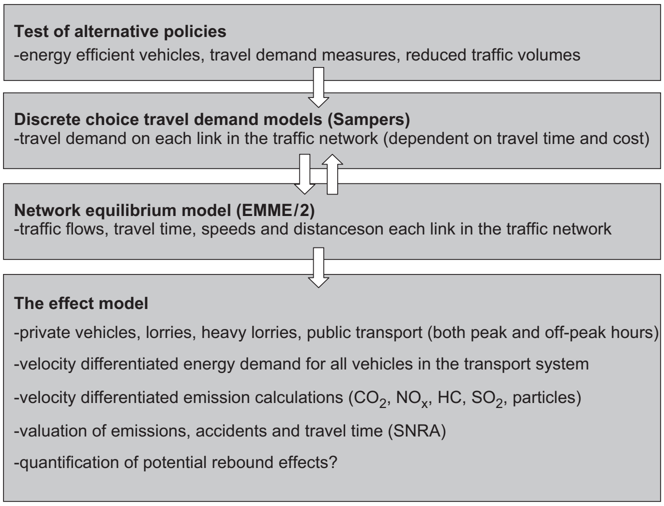

Fig. 2. The modelling system SAMPERS and EMME/2 utilised for deriving traffic flows in the Stockholm transport system. The effect model is designed to calculate energy demand in the transport system as dependent on specific policy measures and energy efficiencies at macroscopic scale.

transport network, incorporating velocities at each road link (causing differentiated combustion at different velocities) and traffic loads at peak and off-peak hours for all different vehicle types (private vehicles, vans, heavy lorries). Data on fuel consumption for different vehicle types at different velocities are taken from the Swedish national road administration [60,61].

Fig. 2 shows the transport modelling system SAMPERS and EMME/2, together with the effect model.

2.3.2. Modelling scenarios of the transport system of Stockholm 2030

The following scenarios were investigated:

1. *Business as usual*: In this scenario we assume that the technological development of fuel efficiency standards will follow a modest pace until 2030 and fuel prices will remain quite unchanged from the present level. No specific travel demand measures are introduced.
2. *Tripled fuel price*: Here we test energy demand from the Stockholm transport system if prices on private vehicle fuels undergo a shock increase (0.3 Euro/km). All other aspects are unchanged from the business as usual scenario.
3. *Technological breakthrough*: This scenario presents the effects of a technological breakthrough where energy demand per vehicle is reduced by 70% in comparison to the business as usual scenario. In this scenario an adherent *rebound effect* (i.e. negative side effect) appears from the reduced kilometre costs. The 70% fuel efficiency implies that private vehicle mileage increases, so that 20% of the energy efficiency is lost [26].
4. *Compound strategies*: This scenario is designed through a mix of various policy measures and assumptions regarding technical developments and more efficient urban mobility. Here we assume: (a) fuel prices are relatively high (0.15 Euro/km); (b) introduction of traffic tolls; (c) zero-cost public transport; (d) ten percent reduced private car ownership through less car-dependent urban mobility (e.g. car sharing, public transport, telecommuting, cycling, etc.); (e) a 50% fuel efficiency on private vehicles compared to the business as usual scenario, combined with a fuel tax preventing rebound effects.

In all of these four scenarios, we use assumptions from the regional development plan for Stockholm County in 2030 [62], which predicts an economic growth of 2% per year (causing predictions of increased car ownership as a result of higher household incomes), a population increase of 33% from 1.8 million inhabitants in 2005 to 2.4 million by 2030, slightly more efficient combustion standards in future vehicles and some further developments in the traffic network. Furthermore, we specifically focus on private vehicle travel and personal mobility, keeping traffic volumes from freight transport and commercial vehicles constant in all four scenarios (Table 4). The overall population increase in Sweden is predicted to follow a quite modest pace, increasing from about 9 million today to 10 million in 2030 [63].

There are some results in Table 4 that are worth highlighting. First, we find that in spite of the fact that private vehicle kilometres are lowest by far in the tripled fuel price scenario, energy use is far lower in the last two scenarios. Thus, a single shock increase in private vehicle fuel prices without compensation from technological efficiency or improvements in travel alternatives would harm personal mobility substantially, to the benefit of only modest energy savings. In the compound scenario, energy use from private cars is reduced by 55% in comparison to the base scenario, and private car kilometres are still reduced by only 13%.

The mix of travel demand measures in combination with improvements in travel alternatives and fuel efficiencies would most likely have a substantial effect on energy use without harming requirements on private mobility. Even though energy use from private vehicle transport is lowest in the technological breakthrough scenario, total energy use is still lowest in the compound scenario. This is explained by the significant rebound effect in the technological development scenario: reduced kilometre costs from increased vehicle efficiency induce more and longer private vehicle trips in the traffic network, causing a higher level of congestion and lower velocities. The higher total energy use in the technological development scenario originates from the commercial transport sector, where each lorry uses more energy per kilometre in a more congested traffic network.

Thus, due to potential synergy effects, it is likely that the largest energy efficiencies would be achieved from a variety of measures rather than focusing single-mindedly on one at a time. To launch travel demand measures in combination

Table 4
Calculated total energy use and energy use for private cars in the four different scenarios investigated

Scenario	Energy use total road traffic (TW h/yr)	Energy use private cars (TW h/yr)	Private car kilometres (million km)
Business as usual 2030	8.9	6.0	7.9
Tripled fuel price	6.8	4.5	5.8
Technological breakthrough	5.6	2.3	9.6
Compound strategies	5.4	2.7	6.9

Table 5
Requirements for target fulfilment (yes/no) based on the four macroscopic scenarios of the transport system of Stockholm 2030, in relation to alternative proportions of biomass set aside for the transport sector (65–100%)

Transport scenarios 2030	Biomass proportion set aside for the transport sector (%)			
	65% (5.5 TW h)	70% (5.9 TW h)	80% (6.8 TW h)	100% (8.5 TW h)
Business as usual (8.9 TW h)	No	No	No	No
Tripled fuel price (6.8 TW h)	No	No	Yes	Yes
Technological breakthrough (5.6 TW h)	No	Yes	Yes	Yes
Compounded strategies (5.4 TW h)	Yes	Yes	Yes	Yes

with energy efficiencies would likely induce a shift to public transport and mobility management alternatives, and mitigate negative rebound effects from reduced kilometre costs.

3. Quantitative estimate of strategies meeting the backcasting target

In this section we synthesise results from Section 2 in order to determine the backcasting target in quantitative terms and to derive feasible paths to target fulfilment.

To quantify the proportion of bioenergy available for Stockholm County in relation to national energy demand in Sweden, we make the transparent assumption that current relationships in energy use between regions will persist in 2030. At present, total energy demand in Stockholm County amounts to about 50 TW h of the national figure of 624 TW h shown in Table 1. Thus, we assume that 8% of national bioenergy assets (177 TW h as presented in Section 2.1) are available for Stockholm County.

However, there is one degree of freedom that we would like to bring to attention and analyse explicitly: the proportion of bioenergy assets that must be set aside for the transport sector in order for the biofuel assets to meet with our backcasting target. Table 5 presents a synthesised assessment of requirements for target achievement, based on the findings in Section 2.

The results of the backcasting exercise (Table 5) give two important indications for the future discussion of biomass to transport fuel possibilities in Stockholm. The first result is that with an energy demand of 8.9 TW h (business as usual) the backcasting target would not be achieved even in the unrealistic case of assigning all biomass assets to the transport sector (100% in Table 5). The second important result is that as much as 40% reduction in transport fuel demand may be achieved by a compounded strategy, where a number of policy options are implemented (50% increased fuel price, traffic tolls, free public transport, mechanisms to decrease car ownership, technological improvements). This is the most energy efficient scenario of the four displayed in this study, where the private sector transport fuel use decreases by 55%, meeting requirements for the backcasting target with a 65% biomass proportion set off to the transport sector. It is important to note that this compounded strategy scenario results in a somewhat decreased private car transport, something that would be seen as positive by some people but a strong restriction to others. In the technological break-through scenario, however, a significant increase (8%) is possible and at the same time the total energy use will be reduced by 37%, almost as much as for the compounded scenario. Combinations of the three scenarios, with e.g. tripled fuel prices, a technological breakthrough and the other measures included in the compounded scenario, give possibilities for far higher reductions in transport fuel use than shown in Table 5. There is thus a possibility to stretch the results in Table 5 even more.

Consequently, efficiency and cost sensitiveness will likely have a direct impact on demand and supply of biomass and agricultural pricing in the market. This demonstrates the importance of making rigorous studies of energy efficiency potentials in all energy sectors before making assessments of reasonable distributions of bioenergy. In particular, efficiency assessments are crucial in the planning process in order to keep competition with forest industries and vital needs for food production, to a minimum.

4. Discussion and conclusions

This work highlights the importance of implementing both demand and supply-side policies in order to reduce energy use and greenhouse gas emissions from the transport sector. In the present study, we assume that 70% of agricultural land is dedicated to food production and 30% to bioenergy production (Section 2.1). This is definitely a matter that needs further research, and where studies like this (including studies on other energy sectors) might provide added value to the current literature. For instance, should bioenergy primarily be used in the heating and electricity sector [22], or is it cost-effective to convert bioenergy to biofuels for transport [23,24]? What synergy effects could be expected between energy sectors where solid waste from biofuel production could be used for heating and electricity [38]? To what extent could other types of renewable fuel assets (e.g. wind, hydro, solar and wave energy) contribute to a sustainable future energy demand? Which crops and which cultivation techniques should ultimately be used for biomass energy on agricultural and forest land? Could energy efficiencies from urban mobility, as displayed in this study, make room for relatively higher energy use in other more peripheral provinces of the national transport network?

The whole area represents a multi-stakeholder complex system that deserves extensive systems analysis studies to clarify the prospects. Proper assessment of biomass potentials requires extensive studies at all system levels—i.e. the global, national and local level [24]. In this study we demonstrate the requirements on the Stockholm transport system in 2030 to meet the biofuel potential of a proportionate fraction of Swedish biomass assets. The study is a comparison between energy quantities (supply and demand), where we make the modest assumption of a 60% conversion efficiency from biomass to biofuel in 2030 [37–40].

The backcasting methodology as such is designed for more robust analyses of desirable futures, to assess resource constraints of such futures, and to discuss optional investment paths in order to identify those that are strategically useful from a systems perspective. In this study, the target is used to: (a) demonstrate the potential of biofuels in Sweden without bringing into many degrees of freedom coupled to potentials for other renewable energy sources and (b) simulate the potential and requirements on energy efficiencies in the transport sector after peak oil, where resource depletion and ecological threats (oil reserve depletion, greenhouse gas emissions from fossil fuels) would foster a rapid technical development and more fuel efficient vehicles. The 50% improved energy efficiencies reviewed in Section 2.2 are not visionary, considering that Sweden, and Stockholm in particular, currently has a relatively high per capita energy use for transport in an international context [57]. In Stockholm, every fourth car weighs more than 1.5 ton, with an engine capacity of more than 158 horsepower, which is well above the Swedish average [64].

Furthermore, one objective of this study is to demonstrate the applicability of traffic modelling in the assessment of energy demand at macroscale. Without a comprehensive transport modelling approach, it is impossible to quantify potential rebound effects adherent to energy efficient vehicles, and how these could be counteracted by specific travel demand measures.

Compound urban planning strategies, where all three components A, B and C are well integrated and consciously calculated together, will hopefully emerge as an important field of knowledge worldwide. Viewed from a governmental policy perspective, aiming at an energy efficient infrastructure, broad investments in combinations of *sets* of measures would likely be more advisable even for other reasons. First, from a backcasting perspective using a predefined principle target, a large bundle of policy measures might be used strategically where one measure might help finance the other (i.e. short-term pay-offs from emission taxes and road user-fees might finance subsidies to alternative energy sources, and to more energy efficient mobility or vehicle technologies). Second, from pure risk-averse reasons, it might be more appealing to design policies that involve more than one specific measure, i.e. to avoid putting all the eggs into the same basket.

We find the concept of integrating local energy-balance targets into a backcasting framework fruitful because it illustrates the requirements on target-orientated principle policies in order to not exceed the resource constraints of such, e.g. boundaries of natural capital. Striving for a balance between domestic renewable energy assets on the one hand, and national energy demand on the other, is often overlooked [8].

As displayed in this study, Sweden is a favoured country as regards production of biofuel. However, on a global basis biofuel does not necessarily represent the highest potential for efficient renewable energy supply and might gradually make more room for other energy sources such as solar, wind, hydro and wave power [18]. During a transition period, biofuels would fill an essential strategic role since they constitute a renewable energy platform for both the present infrastructure, as well as for various optional future renewable fuel solutions. Thus, the current demand for biofuels during the transition period of peak oil might well be a window of opportunity for densely forested countries like Sweden.

For industrialised countries with a biomass potential, e.g. Sweden or Canada, it could well be a moral objective to avoid overconsumption of renewable energy assets from the developing countries in order for these regions to manage the energy transition successfully. Nevertheless, the results should not conflict with the positive benefits of interactions between countries and international trade. Assessment of policies targeting a local energy balance might be valuable for regions in the industrialised part of the world, in order to find ways to pull their own weight and to try to direct market forces in a "resource balanced" direction. One thing is clear, however, entirely different regions than those that have been dominant in the petroleum era will assume strategic importance and reap economic rewards as biofuels successively supplant fossil oil. Peak oil is a global dilemma, and the countries taking the lead in adapting to it will have the opportunity to export technology and know-how to other countries as oil prices continue to rise and the need for alternative energy systems becomes acute.

Finally, few countries now disregard the global threat of climate change. There are indications that we might well approach a tipping point where unexpected climate shifts appear as a cause of the temperature increase, potentially causing great costs from devastating storms, floods, droughts and poor harvests. This uncertainty will likely continue to motivate initiatives toward renewable energy systems.

Appendix A. The effect model

We derive energy quantities generated in the road network from the following relationship:

$$E_j^* = \sum_i \sum_k f_{ik}^* l_i \beta_k \gamma_k(v_i^*), \qquad (1)$$

where E_j^* is the energy demand from the transport network in Stockholm per hour. The superscript * represents peak hours (PH) and off-peak hours (OPH), i the link number, k the vehicle type (private cars, vans and light lorries, heavy lorries, articulated lorries), f_{ik}^* the flow of vehicle type k on link i per hour, l_i the length of link i, β_k the factor compensating for different proportions of petrol-driven and diesel-driven private vehicles in the road network for vehicle type k [39]. Equals 1 for lorries, $\gamma_k(v_i^*)$ the energy demand for vehicle type k at vehicle speed v at link i for PH and OPH, respectively [38].

To calculate daily and annual energy demand from the transport network of Stockholm, we use an approximation applied by the Swedish National Road Administration [38]:

$$E_{j,year} = 365^*(4E_j^{PH} + 10E_j^{OPH}), \qquad (2)$$

where E_j^{PH} is the energy per hour at PH, and E_j^{OP} the energy per hour at OPH.

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