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ORIGINAL ARTICLE

Energy requirement and environmental impact in timber transport

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Abstract

Transportation of timber from forests to industrial sites consumes more fossil fuels than any other part of the Swedish wood supply chain. This paper compares the environmental performance and energy requirements of a range of possible long-distance transport strategies involving lorry or lorry-and-train combinations using a variety of potential fuels/energy carriers, including diesel-oil, coal, hydropower, nuclear fuel and biofuels. The total efficiency of the complete system (i.e. "well-to-wheel" efficiency) is considered. The results indicate that transport alternatives including railway transport require less process energy than options relying exclusively on road vehicles. However, calculations showed that by using biofuels instead of fossil fuel in a lorry, it is possible to replace 96% of the fossil energy.

Keywords: *Biofuel, energy efficiency, ethanol, fossil energy, FTD-fuel, methanol, process energy.*

Introduction

Owing to an expected scarcity of easily available fossil fuels, and the threats posed by global warming, the European Community has provided a strategy for increasing the proportion of renewable energy sources from 6% in 1997 to 12% in 2010 (European Parliament, 2001). From a national perspective, transport accounted for approximately 65% of the overall use of oil products in Sweden in 2002 (National Energy Administration, 2003). Approximately 20% of all domestic transport by lorry in Sweden is related to the forest industry (Swedish Institute for Transport and Communications Analysis., 2004). Berg and Lindholm (2005) showed that in the wood supply chain, from raising seedlings through to timber delivery, long-distance transport of the timber to processing sites (secondary transport) accounts for the largest proportion of energy used (54%, compared with 35% by logging and 11% by silviculture).

A key factor is the kind of fuel that powers the vehicles. Given the expected future scarcity of fossil fuels, and potential consequences of global warming, it is important to look for alternative energy solutions. Biofuels from forest biomass are of interest from a sustainable energy perspective. Furthermore, renewable fuels are considered carbon dioxide (CO_2)-neutral, even though fossil fuels are often required for their production and distribution. However, fossil energy inputs often represent only a small fraction of the total energy inputs in a renewable energy system compared with a fossil energy system (Brandberg, Johansson, & Roth, 1992; Ahlvik & Brandberg, 2001). This conclusion is supported by results published by Arnäs, Blinge, Bäckström, Furnanader, and Hovelius (1997) suggesting that fossil CO_2 emissions are 85–90% lower in bio-based fuel cycles than in comparable fossil fuel cycles.

The main objectives of the study reported here were to quantify the environmental performance and energy requirements of a range of possible long-distance transport strategies. These involve lorry or lorry-and-train combinations using a variety of potential fuels/energy carriers, including diesel-oil, coal, hydropower, nuclear fuel and biofuels such as ethanol, methanol and Fischer-Tropsch Diesel (FTD)-fuel. To evaluate the different fuels, the total efficiency of each complete system is considered, from extraction of energy carriers to their use, usually referred to as their "well-to-wheel" efficiency.

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Ethanol, methanol and FTD-fuel were chosen as alternatives since they all are considered to have future potential as motor fuels (Ahlvik & Brandberg, 2001), especially methanol, according to Hamelink and Faaij (2002). The production price of biofuels (methanol and FTD-fuel) is high, and likely to remain high in the short term (US \$9–16 GJ^{-1}) compared with diesel (US \$7 GJ^{-1}) (Hamelinch & Faaij, 2002; Tijmensen, Faaij, Hamelinck, & van Hardeveld, 2002). In the long term the price could drop as the scale of production increases and process techniques advance. Optimal solutions for reducing the consumption of fossil energy will probably involve the use of several different types of energy carriers, produced from a wide spectrum of feedstocks that are either appropriate for the currently available distribution infrastructure, or so energy efficient that constructing a new infrastructure would be cost-effective.

Materials and methods

The whole fuel cycle of each transport scenario was considered, from extraction of energy carriers through to final use. The measurements used to compare the scenarios were (1) the amount and efficiency of energy inputs into the fuel cycle and (2) the emissions that have a potential global warming effect, acidifying and eutrophying compounds and gases contributing to the creation of photochemical ozone.

Scenarios and system components

Nine different scenarios for the transport systems were compared. The system's functional unit was the transport of 100,000 m^3 of solid wood under bark (m^3 s.u.b.) from the forest in north-western Sweden to a timber terminal on the eastern coast of Sweden. In Figure 1, the base scenario (scenario A) is based on an actual transport solution: the roundwood was loaded onto a lorry at the forest roadside (1) and transported 50 km to a timber station (2), where the roundwood was unloaded and loaded onto a railway train. The railway was first diesel–electric, 121 km (3), then electric, 106 km (4), and again diesel–electric for the last part (2 km) to the timber central on the coast (5).

The other eight scenarios, B1–C4, presented in Figure 1, start as scenario A in the forest, where the roundwood was loaded onto a lorry. The roundwood loads were thereafter either transported directly by lorry to the timber central on the coast, 178 km, or transported by road, 50 km, to the timber station, where the roundwood was reloaded onto a train and transported 229 km to the timber central on the coast. The systems involved a number of types of transport with different maximum loads and energy use (Table I).

All lorries and trains were loaded and unloaded by an independent loader. Loading in the forest needed 158 MJ per lorry and unloading 123 MJ per lorry (Forsberg, 2002). Scaling the timber was done once for each lorry load (7 MJ) (Forsberg, 2002).

The fuel for the lorries was diesel, FTD-fuel, ethanol (EtOH) or methanol (MeOH). Diesel–electric and electric engines drove the trains. Three kinds of electricity were included: the Swedish average electricity mix, Swedish hydroelectric (a "green" alternative) and coal power electricity (Swedish marginal electricity).

Data sources and assumptions

Two companies operating in the area provided average annual values for the fuel consumption of their lorries (0.56 litre diesel or 19.7 MJ km^{-1}), loading factors (50%) for lorries and trains, and the green density of the timber (0.87 t m^{-3} s.u.b.). The loading factor of 50% is attributable to the combination of full loads being taken to the timber terminal, and empty return trips. For trains, the energy used figures are based on experts' estimated values (Andersson, 1994; NTM, 2004). The study did not include the production of capital goods (machinery), since the objective of study was to evaluate differences in energy efficiency and transport strategies.

The estimates of exhaust emissions from the lorries and trains are based on data published by the Network for Transport and the Environment (NTM, 2004). Lorry engines were assumed to fulfil Euro 2 certification norms. Values for carbon monoxide (CO), nitrogen oxide (NO_x) and hydrocarbon (HC) emissions from tractors used in loading were obtained from Hansson, Burström, Norén, and Bohm (1998). The CO_2 output from diesel engines amounts to 2.6 kg l^{-1}, according to the NTM (2004). For all three engines (lorry, train and tractor), estimated nitrous oxide (N_2O) and methane (CH_4) emissions were according to "heavy lorry" figures published by Uppenberg et al. (2001).

Westerholm, Christensen, Törnquist, Ehrenberg, and Haupt (1997) and Nord and Haupt (2002) provide estimates of EtOH and FTD-fuel, and Löfgren (2003) provides estimates for FTD-fuel combustion in working machines. Neither of these was considered to be relevant in this case since they were not specific enough or not applicable to lorries. The emissions from the combustion of biofuels were approximated as being the same as those from diesel, except for CO_2, which was set to zero, and sulfur

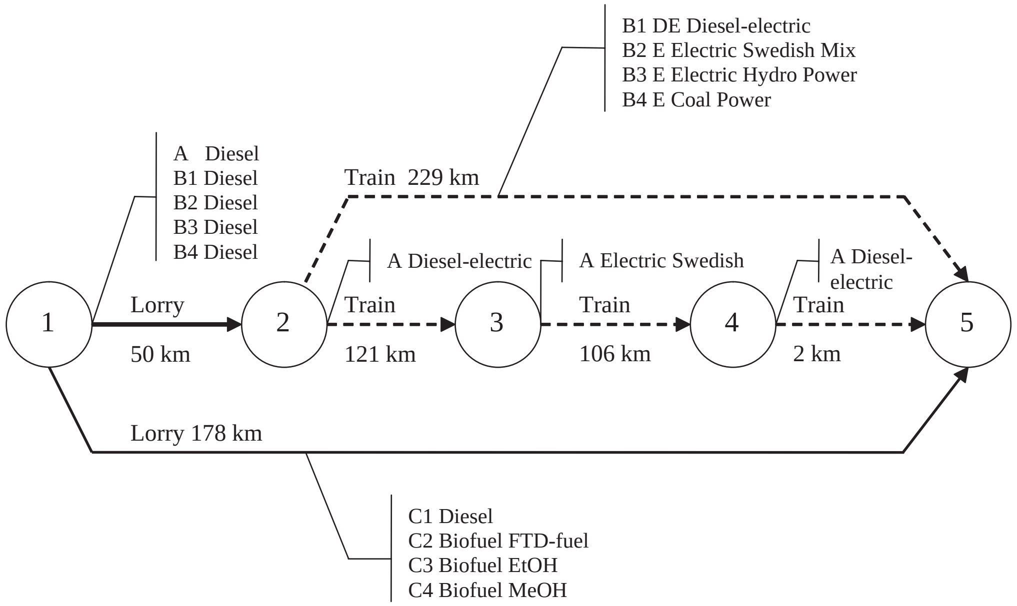

Figure 1. Transport scenarios. A = base scenario (the current transport solution); B1–C4 = alternative scenarios.

oxide (SO_x), which was based on the sulfur content in the fuel. It was assumed that the sulfur content was according to OK/Q8 for diesel and that E85 (85% ethanol, about 15% petrol) could represent all biofuels. The sulfur content in OK/Q8 diesel and E85 (85% ethanol, about 15% petrol) was 10 ppm (Anon., 2004*a*) and 5 ppm (Anon., 2004*b*), respectively.

Energy carriers

Figures related to the energy inputs for producing the energy carriers were taken from Frischknecht, Knoepfel, and Hofstetter (1996) for diesel and petrol oil, Brännström-Norberg, Dethlefsen, and Johansson (1996) for the Swedish electricity mix and hydropower, and Frees and Pedersen Weidema (1998) for coal power. Brännström-Norberg et al. (1996) did not include the conversion losses in the nuclear power plants, which amounted to about 66% in 2002 in Sweden (National Energy Administration, 2003). Berg and Lindholm (2005) provided data for Swedish forest biomass production and Ahlvik and Brandberg (2001) provided production values for EtOH, MeOH and FTD-fuel (Table II). In terms of energy, the production plants were self-sustaining, indicating that the process energy in the plants is of the same origin as the feedstock energy. There was no recovery of low-grade heat from the production plants. To analyse the energy inputs in the scenarios, the resources used for carrying energy were transformed into energy units on the basis of the energy values listed in Table III. Masses of uranium were converted into energy units

Table I. Load and energy use parameters for the different types of transport.

Means of transport	Maximum load (m^3 s.u.b.)	Energy use (MJ tonkm^{-1})	Energy use (MJ m^3 s.u.b. km^{-1})	No. of loadings/ unloadings
Road transport by lorry	47.1[a]	0.99	0.85[b]	2125[f]
Rail trip (diesel electric)	883[c]	0.32	0.28[d]	4250[g]
Rail trip (electricity)	883[c]	0.23	0.20[e]	4250[g]

Note: [a]The maximum loading mass for a rig is 40 t (the gross mass for a lorry is 60 t); [b] Berg and Egebäck (1997) indicate that the fuel use in lorries is the same in terms of energy units. It was assumed that the same energy relationship was valid for biofuels; [c] the maximum load of each railway carriage is 34.8 t (wagon mass: 10.2 t and the locomotive 72 t). Railway requirements limit the number of carriages to 22 per locomotive; [d] the fuel use was 3.5 l km^{-1} (NTM, 2004); [e] the electricity use was 0.076 MJ tonkm^{-1} in an empty train and 0.17 MJ tonkm^{-1} in a train with a load of 448 t (Andersson, 1994); here related to the load of 766 t (883 m^3 s.u.b.) and a loading factor of 50%; [f] number required to transport 100,000 m^3 s.u.b.; [g] as a simplification the loading and unloading are calculated in the units of lorries and the energy consumption is assumed to be the same as for lorries.

Table II. Energy inputs for the production and transport of fuel (MJ MJ^{-1} fuel).

	Feedstock production[a]		Transport of feedstock[a]		Production[b]		Distribution[b]		Total production and distribution			
	Foss[c]	Bio[c]	Foss	Bio	Foss	Bio	Foss	Bio	Foss	Bio	Total	η^{d}_{tot}
Ethanol	0.012		0.014			1.15	0.015		0.041	1.15	1.19	0.46
Methanol	0.009		0.010			0.85	0.020		0.039	0.85	0.89	0.53
FTD-fuel	0.012		0.010			1.22	0.023		0.046	1.22	1.27	0.44
Diesel[e]									0.066		0.066	0.94

Note: [a]data on transport and production of feedstock (biomass) from Berg and Lindholm (2005); [b] data on production and distribution of fuel from Ahlvik and Brandberg (2001) Foss = fossil, Bio = biomass; [d] η_{tot}, energy efficiency = energy content in produced fuel/(energy inputs + energy content in produced fuel); [e] data on diesel production from Frischknecht et al. (1996).
No dimension = no unit.

under the assumption that 1.24 g of uranium ore gives 1 kWh of energy (Brännström-Norberg et al., 1996).

Environmental impacts of emissions

Energy use in transport systems impacts the environment via diverse effects by release of emissions that have a potential global warming effect, acidifying and eutrophying compounds and gases that create photochemical ozone. Therefore, the potential effects of the emissions from the entire energy cycle of each transport scenario were calculated to assess their environmental impact.

Global warming potentials (GWP) were calculated by giving fossil CO_2 a factor of 1, N_2O a factor of 310, CH_4 a factor of 21 and halocarbons factors ranging from 100 to 12,000, according to data provided by the Intergovernmental Panel of Climate Change (IPCC, 1996).

Emissions that are considered to have potentially acidifying effects include nitrogen oxides (NO_x), sulfur oxides (SO_x) and hydrochloric acid (HCl). The Swedish Environmental Management Council (SEMC) uses an indicator for acidification that is based on the potential stoichiometric formation of hydrogen ions (H^+) from each type of emission (Lindfors et al., 1995).

Table III. Energy content of energy carriers.

Energy carrier	Gross calorific value (MJ kg^{-1} D.S.)	References
Coal	27.2	Anon. (1998); Uppenberg et al. (2001)
Crude oil	42.7	Anon. (1998)
Diesel (EC-1)[a]	43.2	Uppenberg et al. (2001)
Ethanol	26.8	Anon. (1998); Uppenberg et al. (2001)
Lignite	14.7	Anon. (2004*c*)
Methanol	19.7	Anon. (1998)
Natural gas	51.9	Anon. (1998); Uppenberg et al. (2001)
FTD-fuel	46.7	Nord and Haupt (2002)
Wood biomass	19.2	Anon. (1998); Uppenberg et al. (2001)

Note: [a]Swedish environment class 1, indicating low levels of sulfur and polyaromatic hydrocarbons.

Organic compounds and phosphorus released to water, and emissions of nitrogenous compounds to both air and water, are the most serious eutrophication agents. The estimated eutrophication potential of the emitted compounds is based on the amount of oxygen consumed in the mineralization of organic material that they induce (SEMC, 2000).

Photochemical ozone is harmful to living organisms. The indicator used to estimate amounts of such reagents is the photochemical ozone creation potential (POCP) (SEMC, 2000). The most important gases in this respect are ozone (O_3), nitrogen dioxide (NO_2) and organic oxidants such as aldehydes and peroxides.

Sensitivity analysis

Forsberg and Löfroth (2002) found that by teaching lorry drivers fuel-efficient driving techniques the fuel use in lorries could be decreased by 10%. Furthermore, the road surface induced a 25–70% higher fuel use in lorries on forest roads and small roads than on larger roads. Therefore, a 20% decrease in fuel use in lorries was tested in a sensitivity analysis. In addition, a 50% increase in the energy used for extracting and processing diesel oil was tested, owing to the expectation that oil resources will become increasingly difficult to access in the future.

Results

The specification of results parameters is presented in Table IV. Both the process energy and the primary energy were lower in scenarios that included a freight train (A, B1–B3) than in those that only used lorries (C1–C4), except for the train powered by electricity

Table IV. Specification of result parameters.

	Result parameters	Definition
Input	Primary energy	Production and distribution energy of energy carriers and process energy in the scenarios
	Process energy	Energy input required to operate a process excluding energy inputs for production and delivery of this energy
	Energy efficiency	Process energy/primary energy
Output (product)	Transport of 100,000 m^3 s.u.b.	Functional unit
Output (emissions)	Global warming potentials (GWP) Acidification (mol H^+) Eutrophication (g O_2) Photochemical ozone creation potentials (POCP)	

from coal power (scenario B4, Table V). In scenarios B1, B4 and C1 (lorry, diesel), no renewable energy was included in the fuel cycle. In contrast, scenarios C2, C3 and C4 only used 3–4% fossil energy, and renewable energy accounted for the rest.

Scenarios B4, C2, C3 and C4 all had low efficiency (37–56%) compared with other alternatives, which had efficiency levels of 76–94%. However, in terms of process energy/fossil energy input ratios the rankings are entirely different: scenarios C2, C3 and C4 have by far the highest ratios, since they require the least inputs of fossil fuels. Scenario B4 (electric train, coal power, with a small diesel lorry component) had the lowest energy efficiency and process energy/fossil energy ratio.

Environmental effects of emissions

The biofuelled lorry transport scenarios (C2, C3 and C4) had the lowest potential global warming impact, generating only 15% of the base scenario A and 8% of the diesel-fuelled lorry alternative (scenario C1, Table VI). Scenarios B2 and B3, based on electric trains, had the lowest potential eutrophication and acidifying impact (Table VI). The potential release of gases creating photochemical ozone was small from scenarios involving a minor use of diesel, namely those based largely on electric trains (B2, B3 and B4) and those based on biofuelled lorry transport (C2, C3 and C4).

Sensitivity analysis

A 50% increase in energy use for extracting and processing diesel oil resulted in increased energy inputs and increased the environmental impact in almost all cases (Table VII). A 20% reduction in fuel consumption in lorries owing to smoother driving and better road surfaces reduced energy inputs and environmental effects (Table VIII).

Discussion

Primary and process energy requirements were lower for rail than for road (lorry) transport, except for the train powered by electricity from coal power. The potential impact of acidification and eutrophication was also lower for rail powered by electricity than for road. Although the maximum load on a train as a proportion of the overall vehicle weight is larger, and consequently trains are more efficient than lorries, the transport distance is further for trains. However, scenarios involving lorry transport based on biofuels had low potential impact of global warming and

Table V. Primary energy, process energy, energy efficiency, renewable component of primary energy and the ratio for process energy/fossil energy input.

	Primary energy (TJ)	Process energy (TJ)	Energy efficiency = Process energy/primary energy (%)	Renewable part of primary energy (%)	Process energy/fossil energy input (%)
A	11.7	10.7	91	18	111
B1	12.9	11.5	89	0	89
B2	12.7	9.6	76	19	121
B3	10.2	9.6	94	44	169
B4	25.9	9.6	37	0	37
C1	17.7	15.7	89	0	89
C2	36.0	15.7	47	97	1357
C3	35.2	15.7	49	96	1246
C4	30.5	15.7	56	96	1343

Table VI. Potential environmental impacts of the transport scenarios.

Scenario	Global warming (t GWP)	Acidification (kmol H^+)	Eutrophication (kt O_2 potentials)	POCP
A	808	236	58	938
B1	1100	347	87	1290
B2	526	110	26	541
B3	468	106	25	535
B4	1630	229	42	591
C1	1440	300	70	1610
C2	118	251	68	378
C3	129	253	68	390
C4	121	251	68	380

Note: GWP = global warming potential; POCP = photochemical ozone creation.

gases creating photochemical ozone. In addition, the renewable energy fraction was higher in scenarios involving lorry transport based on biofuels than in railway transport. It should be emphasized that the energy inflow in scenario B2 (train, Swedish power mix, with a small diesel lorry component) would have been higher if the conversion losses (heat) from the nuclear power had been included.

Scenario B4 (electric train, coal power, with a small diesel lorry component) had the lowest energy efficiency, followed by the biofuel scenarios. The pattern is the opposite for primary energy inputs, since the biofuel scenarios and scenario B4 had the highest level of primary energy. This is due to the nature (i.e. low energy density) and/or imbalances in current technological capacities (i.e. the relatively low processing and combustion efficiency of biofuels and coal compared with other energy carriers such as diesel or hydroelectricity). However, when the energy efficiency calculations were based on fossil energy inputs, the scenarios involving renewable energy (C2, C3 and C4) had by far the greatest efficiency.

The present European Union policy (European Parliament, 2001) on renewable fuels makes it important for the forestry sector to consider the scope for using renewable fuels. In this case study, the results reveal that fossil energy accounts for just 3–4% of the primary energy in scenarios where biofuels supply 100% of the process energy, which is consistent with the findings of Brandberg et al. (1992) and Ahlvik and Brandberg (2001). This indicates that about 82% of the fossil energy could be replaced with bioenergy compared with the base scenario A, and 96% if the comparison is made between the lorry scenarios with diesel and biofuel.

Environmental effects of emissions

The low environmental impact of scenarios based largely on electric train transport (B2–B3), with the exception of scenario B4 (diesel and electric train, coal power, with a small lorry component) is due to the processes used to generate electricity. Nuclear power and hydroelectric power generation cause no combustion emissions, such as those produced in scenarios involving the combustion of oil, coal or biomass. Emissions formed in the hydroelectric and nuclear power energy cycles arise from additional energy carriers used in power processing. However, hydroelectric and nuclear power generation is associated with other environmental problems, such as

Table VII. Increases in primary energy and environmental effects due to a 50% increase in energy requirements for extracting and processing diesel oil.

Scenario	Relative change in primary energy (%)	Global warming (%)	Acidification (%)	Eutrophication (%)	Photochemical ozone creation (%)
A	5.3	1.1	0.85	0.34	5.5
B1	6.6	0.91	1.2	0.46	5.4
B2	3.0	1.1	0.9	0.78	5.7
B3	3.7	1.3	1.9	0.40	5.8
B4	1.5	0.0	0.9	0.48	5.1
C1	6.5	1.3	1.6	0.72	6.2
C2	0.2	1.7	0.4	0	1.9
C3	0.27	0.8	0	0	1.8
C4	0.29	0.83	0	0.15	1.8

Table VIII. Reductions in primary energy and environmental effects due to a 20% decline in fuel consumption in lorries.

Scenario	Relative change in primary energy (%)	Global warming (%)	Acidification (%)	Eutrophication (%)	Photochemical ozone creation (%)
A	−8.9	−1.7	−1.7	−0.86	−7.7
B1	−7.6	−0.91	−1.2	−0.46	−6.2
B2	−7.8	−2.5	−3.6	−1.6	−13
B3	−9.8	−2.8	−3.8	−1.6	−13
B4	−3.7	−1.2	−1.7	−0.96	−12
C1	−23	−3.5	−4.7	−2.1	−16
C2	−23	−16	−1.6	−1.6	−5.8
C3	−23	−17	−2.0	−1.8	−6.4
C4	−23	−17	−2.0	−1.5	−6.1

damage to the ecosystem due to dams and mining, which were not evaluated in this study.

Strong effects in all impact categories were found in the scenarios entailing major use of diesel oil, such as scenarios A, B1 (diesel-electric train, with a small diesel lorry component) and C1 (diesel lorry). The results revealed that acidification and eutrophication were related to emissions formed in the combustion process of energy carriers such as diesel, biofuels and coal. Emissions of gases creating photochemical ozone were mostly related to the production of diesel fuel. The potential global warming impact was related to the fossil energy components of the fuel input, and could be decreased by changing process energy.

The sensitivity analysis

The sensitivity analysis showed that the scenarios depending on fossil diesel, naturally, were most sensitive to increases in the energy requirements for extraction, and the most pronounced changes (increases of about 1.5–6%) occurred in the photochemical ozone-creating parameter, owing to its relationship to diesel production. The effect of decreasing fuel consumption in lorries had a major influence on the primary energy input in the scenarios based on lorry transport, reducing them by about 24%.

Data quality

Data quality in this context is dependent on source, time and relevance to the technical system studied. Different data sources cause variation and uncertainty. For example, the production values of biofuels from Ahlvik and Brandberg (2001) are not representative to biofuel production today; rather, the data reflect future scenarios of 2012. Nevertheless, the authors of this paper believe that such an approach gives a more realistic potential for biofuels compared with conventional fuels.

Various criteria have not been investigated in this study, e.g. the cost of fuel production, distribution and end use. Many other environmental and social aspects have not been included, as they were beyond the scope of this study.

Conclusion

This study does not unambiguously identify environmentally optimal scenarios. However, it is easy to identify scenarios that should be avoided since the energy efficiency is low and the potential environmental impact is high. Such scenarios are those that include the use of coal power and fossil diesel. This placed the emphasis on the energy carrier in the system, fossil fuel or renewable biofuel, rather than the technical transportation means itself, by railway or road vehicle.

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