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Energy consumption and related air pollution for Scandinavian electric passenger trains

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Abstract

Energy consumption of a number of modern Scandinavian electric passenger train operations is studied. The trains are *X 2000*, *Regina*, *OTU* (Øresundstoget), *Type 71* "Flytoget" and *Type 73* "Signatur". Energy measurements are made in regular train operations in Sweden, Denmark and Norway. For *Regina* and *Flytoget* long time series (at least one year) are available, while shorter time series are available for the other train types. Energy data for new trains (introduced since 1999) are collected in the years 2002-2005. Energy data from 1994 are used for *X 2000* and are corrected for operational conditions of 2004. For comparison, energy data for an older loco-hauled train of 1994 is also used.

In the present study energy consumption for propulsion, on-board comfort and catering, as well as idling outside scheduled service, is determined. The energy consumption includes losses in the railway's electrical supply, i.e. the determined amount of energy is as supplied from the public electrical grid.

Emissions of air pollutants, due to production of the electric energy used, are also determined, in this case CO_2, NO_x, HC and CO. Three alternative determinations are made:

(1) Pollution from *average* electric energy on the common Nordic market;
(2) Pollution from *"Green"* electric energy from renewable sources;
(3) *Margina*l contribution for an additional train or passenger, short-term and long-term. The newly introduced EU Emissions Trading Scheme with emission allowances will most likely limit the long-term emissions independently of the actual amount of electric energy used by electric trains.

It is shown that the investigated modern passenger train operations of years 2002- 2005 use a quite modest amount of energy, in spite of the higher speeds compared with trains of 1994. For comparable operations the energy consumption is reduced by typically 25 – 30 % per seat-km or per passenger-km if compared with the older loco-hauled trains. The reasons for the improved energy performance are:

(1) Improved aerodynamics compared with older trains (reduced air drag);
(2) Regenerative braking (i.e. energy is recovered when braking the train);
(3) Lower train mass per seat;
(4) Improved energy efficiency in power supply, partly due to more advanced technologies of the trains.

Energy consumption per passenger-km is very dependent of the actual load factor (i.e. ratio between the number of passenger-km and the offered number of seat-km). For long-distance operations load factors are quite high, typically 55 - 60 % in Scandinavia. In this market segment energy consumption is determined to around 0.08 kWh per pass-km. For fast regional services with electric trains, the load factors vary from typically 20 to about 40 %, while the energy consumption varies from 0.07 kWh per pass-km (for the highest load factor) to 0.18 kWh/pass-km.

However, also in the latter cases the investigated trains are very competitive to other modes of transport with regard to energy consumption and emissions of air pollutants.

Preface and acknowledgements

This energy study was initiated in an agreement between Bombardier Transportation and the Royal Institute of Technology (KTH) in Stockholm. It is a “follow-up” and continuation of a similar energy study made at KTH in 1994. The main part of the study has been made at KTH, using energy data supplied from various sources.

First of all the personal and financial support from the Centre of Competence “Design for Environment” at Bombardier Transportation is gratefully acknowledged. In particular we would bring our thanks to Mrs Christina Larsson, Mrs Sara Paulsson and Mr Peder Flykt for their enthusiastic and very valuable personal support in supplying energy data from *Regina* and *X 2000* trains and in their efforts to arrange the necessary contacts with train operating companies in Scandinavia.

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Stockholm in June 2006

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Content

Definitions and explanations

In alphabetical order

Carbody tilt	The carbody of the train (i.e. the part containing the payload) is tilted inwards when running in curves thus reducing lateral forces on passengers. Carbody tilt is an important prerequisite for allowing the train to negotiate curves at higher speeds than normal trains.
Catenary	The overhead electrical cable supplying electric power to the current collector (pantograph) of an electrically powered train. The pantograph stays in continuous contact with the catenary. Sometimes the catenary is known as the *contact cable* or *contact wire*.
CHP (Combined Heat and Power)	Electric power (energy) produced by using steam turbines where the steam is finally condensed at a (comparatively) high temperature, allowing the heat of the water to be utilised for district heating or industrial purposes. Thus most of the inherent energy can be utilised either as electric power or as useful heat. Compare "*Condensing power*" below.
Condensing (electric) power	Electric power (energy) produced by using steam turbines where the steam is finally condensed by cooling with low-temperature water, implying that the heat of the water can usually not be utilised. Thus most of the inherent remaining energy (after electric power generation) is lost to the water. Compare "*CHP*" above.
Converter station (for railway)	Facility with appropriate equipment for converting electric three-phase alternating electric power from the public electrical grid (frequency 50 Hz) to the frequency and voltage used by the trains, and thus be fed into the catenary. In Sweden and Norway trains use single phase alternating current with a frequency of 16 2/3 Hz while the voltage is nominally 15 kV. In Denmark (and Finland) the frequency is 50 Hz and the voltage 25 kV. On other networks direct current (i.e. not alternating current) may be used in combination with a lower voltage.

Electric power	Electric energy
Energy consumption	In the context of the present study, energy consumption means e.g. *energy utilization* or *energy usage*. Energy can not be “consumed”, only utilized or converted between different kinds of energy, e.g. chemical energy (in fuels), kinetic energy, potential energy, heat, electric energy etc. The term ‘energy consumption’ is used because it is common terminology in the railway sector.
Energy recovery	Electric energy is fed back to the catenary, while the train is braking or running downhill. Thus some part of the energy intake is recovered. See also “*Regenerative braking”* below.
Load factor	The ratio between the number of passenger-km and the offered number of seat-km. Load factor is sometimes called *seat occupancy rate*.
Nordic countries	*Denmark, Finland, Iceland, Norway* and *Sweden*. In the context of this study Iceland is excluded.
Pantograph	The current collector on an electrically powered train, in contact with the catenary.
Regenerative braking	The electric motors for propulsion are switched over to working as electric generators, thus generating electric power when producing a braking effort on the train. Compare also “*Energy recovery*” above.
Scandinavia	In the context of this study it is *Denmark, Norway* and *Sweden.*
Tilt	See “*carbody tilt”* above.

Abbreviations and names

Banverket	The *Swedish National Rail Administration*, reporting to the minister of transport. Banverket is responsible for the Swedish rail infrastructure and is also an agency for the whole railway sector in Sweden.
Bombardier Transportation	Global manufacturer and supplier of trains and other railway equipment, with the main office being located in Canada. Facilities for development and manufacturing are located around the world, like in Sweden, Germany, France, UK, Austria, Switzerland, China, USA, Australia etc.
DSB	*Danish State Railways*.
EMU	*"Electric Multiple Unit*", an electrically powered train of motor coach type, i.e. with propulsion equipment located in the same coaches as the payload, i.e. this type of train has *no* separate locomotive heading the train.
ETS	EU *Emissions Trading Scheme*: Emissions of greenhouse gases in Europe is limited by a fixed and gradually decreasing allowances. If one entity is not able to reduce its emissions, or wants to even increase them, that entity must buy allowances from another entity being able to reduce emissions at a cost less than the price of the transferred allowances. See further Section 2.4.2.
Flytoget	An electrically powered EMU train, mainly used by the company *Flytoget AS* for fast rail services between the airport Gardermoen, Oslo and Asker. The train hardware is quite similar to the train type *Signatur*; see below. Flytoget is officially designated as "*Type 71*". See also Figure 1-4.
KTH	*Kungliga Tekniska Högskolan* – in English called the Royal Institute of Technology, located in Stockholm, Sweden. KTH has a centre of excellence for research and academic education in railway engineering. One part of this centre is the Division of Rail Vehicles at the Department of Aeronautical and Vehicle Engineering.
NSB AS	The national passenger rail operator in Norway, emanating from the former Norwegian State Railways.
OTU	*Øresund Train Unit* - an electrically powered EMU train running fast regional services over the Øresund link (including the bridge) between

Sweden and Denmark. This type of trains also extends services to other surrounding areas and railways lines in Denmark and Sweden.
OTU trains are currently operated by DSB and SJ AB. See also Figure 1-3.

Regina An electrically powered EMU train running fast regional services in different areas of Sweden. It is officially designated as X50 – X54 in different versions and is currently operated by *SJ AB* and *Tågkompaniet*, see below. These companies operate the vehicle for various local traffic authorities, such as Upplands Lokatrafik and X-trafik. Regina is a wide-body train; see also Figure 1-2.

Scandinavia In the context of this study it is *Denmark, Norway* and *Sweden.*

Signatur An electrically powered EMU train used by NSB in Norway for long-distance services. It is technically quite similar to the train Flytoget, but Signatur is equipped with carbody tilt. Train type Signatur is officially designated as "*Type 73*". See further Figure 1-5.

SJ AB The largest passenger rail operator in Sweden, emanating from the former Swedish State Railways.

Tågkompaniet *Tågkompaniet i Sverige AB* - An independent passenger rail operator in Sweden.

Upptåget A regional train system formed by the publicly owned regional transit company *Upplands Lokaltrafik (UL)* in 'Uppsala län', Sweden. See further Section 3.3.2.

Vattenfall *Vattenfall AB* – the largest supplier of electric power in Sweden, actively engaged also in other countries.

X-Trafik Publicly owned regional transit company in 'Gävleborgs län', Sweden. See further Section 3.3.2.

X 2000 High-speed tilting train for long-distance passenger services in Sweden. It is equipped with carbody tilt and is used by the operator SJ AB. The train consist is a light-weight locomotive followed by 4 – 6 passenger cars. The train is officially designated as X2. See also Figure 1-1.

1 Introduction

Rail transport is widely considered to be energy efficient compared to most other modes of transport. By consuming just a moderate amount of energy, there are also prospects of low emissions of pollutants into the air, such as carbon dioxide (CO_2), nitric oxides (NO_x) and others. The possibilities to use electric power further strengthen this tendency, because electric power may be produced by a number of means, some of them with very low air pollution, if any. Low energy consumption and air pollution are often considered as being competitive advantages of rail traffic, together with high safety, comfort, high capacity and space efficiency as well as – for modern rail systems – travelling speed.

In 1994 a study was made by KTH (Royal Institute of Technology, Stockholm, Sweden) on energy consumption and air pollution in Swedish electric rail traffic [1]. Different types of trains were investigated through electric energy measurements in various types of passenger and freight services. An estimation of future development (year 2010) was also made. Since that time a number of new modern passenger trains have been introduced in Scandinavia (Denmark, Norway and Sweden), mainly with electric propulsion and to a small extent also with diesel propulsion. Also the services of the high-speed train *X 2000* have been further developed. However, no update of energy and air pollution studies is known since the previous study in 1994.

The present study is initiated by Bombardier Transportation (Sweden). This company has supplied the majority of new trains for Scandinavia during the period 1994 – 2004. For example, by the end of 2004 the following numbers of *electrically powered* passenger vehicles were delivered for main line rail operations:

- 224 cars of the high-speed tilting train *X 2000* as well as 43 power units of the same train for the Swedish rail operator SJ AB (partly delivered before 1994); see Figure 1-1.
- 148 cars of the fast regional trains *Regina* for Swedish domestic services; see Figure 1-2.
- 168 cars of the fast regional trains for the Øresund link between Denmark and Sweden; see Figure 1-3. These train units are often called *OTU (Øresund Train Unit).*
- 48 cars of the trains *Type 71* for Gardermoen airport outside Oslo in Norway, also called *Flytoget*, running airport shuttles between Gardermoen, Oslo and Asker; see Figure 1-4.
- 88 cars of the long-distance tilting trains *Type 73* earlier called *Signatur* and the fast regional trains *Type 73b* earlier called *Agenda* for domestic Norwegian services operated by NSB; see Figure 1-5.

All of these cars are four-axle vehicles each having a length of 25 – 27 m. All the trains have a permissible speed ranging from 180 to 210 km/h. They have all air condition. *X 2000* has a bistro (about half a car) as well as the Norwegian *Signatur* trains. Both *X 2000, Signatur* and *Agenda* have carbody tilt, in order to allow increased speeds in curves.

The *OTU* is able to run on both the Danish and Swedish signalling and electrification systems. In Sweden the electrical supply system has a nominal voltage of 15 kV at 16 2/3 Hz. The Danish electrified main lines have a nominal voltage of 25 kV at 50 Hz.

Further train data are given in Figures 1-1 to 1-5.

Figure 1-1   High-speed train X 2000
Power unit + 5 cars + driving trailer
Number of seats, 1+2 class,   98+222 =320
Max speed in service   200 km/h
Mass in running order   366 tonnes

Figure 1-2   Fast regional train "Regina"

2 motor coaches (alternatively with 1 intermediate trailer)
Number of seats, 1+ 2 class, 19 + 148=167, (alt. 19+ 253=272)
Max speed in service   200 km/h
Mass in running order   120 (alt. 165) tonnes
(Numbers within brackets refer to the 3-car version with an intermediate trailer)

Figure 1-3 “Øresundstoget” (OTU)

2 motor coaches + 1 intermediate trailer
Number of seats, 1+ 2 class, 20 + 217 = 237
Max speed in service 180 km/h
Mass in running order 157 tonnes

Figure 1-4 Airport train Type 71 “Flytoget”

3 motor coaches
Number of seats, 2 class = 168
Max speed in service 210 km/h
Mass in running order 168 tonnes

Figure 1-5 Long distance train Type 73 “Signatur”

3 motor coaches + 1 intermediate trailer
Number of seats, 1+ 2 class = 201-227
Max speed in service 210 km/h
Mass in running order 233 tonnes

Scope and limitations of this study

The scope of the present study is to determine average energy consumption and the related emissions of air pollutants of representative modern trains in passenger service in Scandinavia. All the trains studied are supplied by Bombardier Transportation. Some comparisons will also be made with older train services and – to some extent – with other modes of transport.

In order to achieve a figure on average energy consumption – and/or its related air pollution – either measured or simulated energy consumption data are needed, per *train-km* or per *seat-km.* It is also of interest to convert these data into energy or pollution per *passenger-km.* The latter conversion is possible only if the average load factor, i.e. the seat occupancy rate, is known. The load factor is here defined as the number of passenger-km divided by the number of offered seat-km.

Energy consumption and its related air pollution, as determined per seat-km, has a large variation over time for a specific type of train, due to the actual speed or the number of stops. If determined per passenger-km there is also a variation due to the actual load factor. However, it is not the aim of this study to determine energy or pollution data for all possible cases. In this study a number of train services have been selected, all being believed to be representative for the respective types of railway mainline passenger services on average. The characteristics of these services are presented and discussed in Sections 3.2 - 3.6.

A train with electric propulsion consumes energy being produced in some kind of electric power plant. In order to determine the air pollution, indirectly resulting from the electric power production and consumption, the means of electric power production is decisive. Electricity can be produced by means of - for example – hydropower, nuclear power, wind power or some kind of bio-fuels. Electric power can also be produced by fossil fuels like coal, oil or natural gas. The efficiency and energy losses – as well as emissions of air pollutions - in fuel-burning power stations may vary over a quite large range depending on the technology used and whether heat (for district heating or industrial use) is produced or not. The present study also discusses these issues in Sections 2.3 – 2.5.

2 Structure of railway electric energy consumption and its related air pollution

2.1 Structure of energy utilization on railways

2.1.1 Various purposes of energy consumption

There are various purposes of using energy on railways and in train operations. We propose energy consumption in train operations to be divided into *eight different purposes* as shown in Table 2-1. The table is particularly adapted to electric train operations, i.e. the case where electric power is taken from an overhead electrical cable - usually called *catenary* – through the current collector – called *pantograph* – for use in an electrically powered rail vehicle.

1	Propulsion including auxiliary machinery and the necessary safety systems
2	Comfort during the journey
3	Idling outside scheduled service
4	Stationary vehicle heating at parking on stabling tracks - through the ordinary pantograph (i.e. the current collector) or - through a special stationary “heating terminal”, to be connected to the train
5	Complementary runs
6	Maintenance of vehicles
7	Operation and maintenance of fixed installations not including heating of premises
8	Heating of buildings and other premises serving the rail transportation system

Table 2-1 Energy consumption for various purposes
The various purposed are further explained and exemplified in the text sections below.

In this study energy consumption is determined for purposes 1 – 3. In some cases energy for stationary heating at parking (purpose 4) is included in the measured raw data. In such cases energy for purpose 4 is estimated and excluded from reported energy consumption. Energy for purposes 5 – 8 is not regarded at all in this study.

As a transportation system, the railways thus require more available functions than the actual propulsion and hauling of vehicles. Naturally, this also applies to other modes of transport: road, air and sea transportation.

Below are some examples, comments and comparisons given of the various purposes as listed in Table 2-1, for electric rail transportation as well as the corresponding road traffic. The examples presented are, however, not claimed to be a comprehensive list.

1 Propulsion

Railway	*Road*
- The electric energy received via the pantograph (current collector), to drive the train from A to B	- The energy content of the fuel that has to be taken from the fuel tank of the car to drive the vehicle from A to B.
or (as used in this study):	
- The electric energy taken from the public electric power grid, converted and transmitted through the catenary to the train's pantograph, used for driving the trains from A to B. Thus this energy includes losses in the railway's supply system.	- As above, with addition of the energy needed for transportation of the fuel from the fuel refinery to the fuelling station as well as for operation of the fuelling station.

Besides the energy needed for propulsion, the energy required for running the necessary auxiliary machines and all the safety-related equipment (brakes, external lighting, door closure etc.) is included. This is normally the case for both rail and road transport.

2 Comfort during the journey

Railway	*Road*
- Heating	- Heating
- Ventilation and air condition in compartments and drivers cabin	- Ventilation and air conditioning
- Interior lighting	- Interior lighting
- Carbody tilt when negotiating curves at increased speed (where applicable)	
- Haulage and operation of restaurant car, or other catering facility (where applicable)	- (Roadside inn)

Heating, lighting and ventilation are included in the energy consumption reported for trains in this study.

Reported energy consumption of trains also includes carbody tilt equipment as well as haulage and operation of restaurant cars where applicable (in the present study for the trains *X 2000* and *Signatur).*

The restaurant car has no real corresponding facility in road transportation, at least not in private cars. Where a train includes a restaurant car, a normal figure for the additional energy needed for its haulage and operation is usually in the order of 5 – 10 %, although variations exist.

3 Idling outside scheduled service

Railway

- Idling standstill in workshop areas
- Idling standstill before departure
- Idling during station stops

Road

- Idling at preparation, checking and repair
- Idling before departure
- Idling during intermediate stops

Energy consumed at idling outside scheduled service is included in the energy figures reported for trains in this study. The amount of energy needed for this purpose is estimated to around 2 % of the total energy consumption, as an average.

Including idling as above is equivalent of what is normally included in corresponding figures for practical road vehicle operations.

4 Stationary vehicle heating at parking

Railway

- Stationary heating at parking on stabling tracks, electric power supplied from the catenary through the pantograph
- Stationary heating at parking on stabling tracks, electric power supplied from special heating terminals or sockets
- Stationary heating in workshops

Road

- Stationary heating supplied from the ordinary fuel (petrol or diesel)
- Stationary heating supplied from an electrical socket connected to an electrical grid
- Stationary heating in garages

Electric energy for train heating supplied from the catenary and pantograph is in some cases included in the raw data, as measured and stored by the energy meter of the train. However, the energy for such heating is normally not included in energy consumption figures, neither for rail nor road transport. Thus, *the estimated amount of energy for stationary heating is excluded from the energy reported in this study*.

5 Complementary runs

Energy for complementary runs, i.e. propulsion of trains from the stabling tracks or maintenance facilities to the departure tracks, including shunting operations, *is not included in energy consumption data as reported in this study.* This is equivalent as for buses or taxis, where energy consumption for such complementary runs is normally not included. Energy for such runs is sometimes included in the measured raw data for the trains in this study, but in such cases also the corresponding running distance is included. Therefore the measured energy per running distance (kWh per train-km) does not include extra energy for complementary runs.

The amount of energy needed for this purpose is estimated to around 4 % of the total energy consumption, as an average.

6 – 8 Vehicle maintenance, operation and maintenance of fixed installations, heating of buildings and other premises

Energy used for these purposes is not regarded and is *not* included in the energy figures reported in this study. So is usually also the case for road and other modes of transport.

Comments

Although not all purposes of energy consumption are included in the figures reported in this study, this is usually the case for other modes of transport. Moreover, from a scientific point of view, it is most important to know what is included and what is not included.

In addition, the various purposes of energy consumption need various types of electrical equipment, having inherent energy losses. The losses are usually included in the measured (or calculated) amount of energy consumed by the train. However, there is a substantial energy loss in the railway system also before the energy reaches the train, namely in the power supply system of an electric railway. These losses are dealt with in Section 2.2.2 and will be added to the energy consumption as measured at the train (pantograph) level.

2.1.2 Variation by season

Energy consumption of trains exhibits usually a variation by season.

In winter time (December – February) temperatures in Scandinavia have averages reaching from about 0 to -7 °C. The extremes from day to day may be much more varying, in particular on the low side. These temperature conditions are prevailing in the southern half of Scandinavia where most of the electric train operations are performed.

The low temperatures result in an *increased need for heating* in the trains – i.e. an increased amount of *comfort energy* - and thus increased energy consumption both in ordinary train operations and for parking at stabling tracks.

Also in the operating mode the trains will need an increased amount of energy at low temperatures. Firstly doors are opened frequently, in particular on regional and local trains, thus *letting out some amount of heat* which must be compensated for by more heating in the trains. Secondly, *air density will be higher at low temperatures*, *which produces a higher amount of air drag,* proportional to the air density. At the same air pressure the air density is about 10 % higher at -7 ºC than at +20 ºC, thus producing 10 % increased air drag. The latter is particularly important for high-speed trains running at speeds around 200 km/h or more; as these trains have normally more than 50 % of the energy consumption due to air drag. There is likely also an increased air drag due to snow dust and similar, although these effects are not studied in detail.

On the contrary, in late spring, summer and early autumn (May – September), average temperatures are usually in the range of +10 ºC to +20 ºC. The need for comfort energy is at a minimum. Outside temperatures are not far from the desired average inside the train. There is sometimes need for air condition (air cooling) consuming some energy, but this need is usually compensated by less energy needed for heating. At very high temperatures in summer time the energy consumption should increase to some extent due to air cooling, but due to the (normally) short periods of high temperatures in Scandinavia this is not obviously reflected in the monthly count of total energy consumption.

In the present study, energy consumption has been measured in some trains during time periods of up to three years. Figure 2-1 shows an example of such a time series of energy consumption. It is measured on six *Regina* trains in regional service for *X-Trafik* in Sweden (see further Section 3.3.2) [14]. The tendencies described above are quite clear.

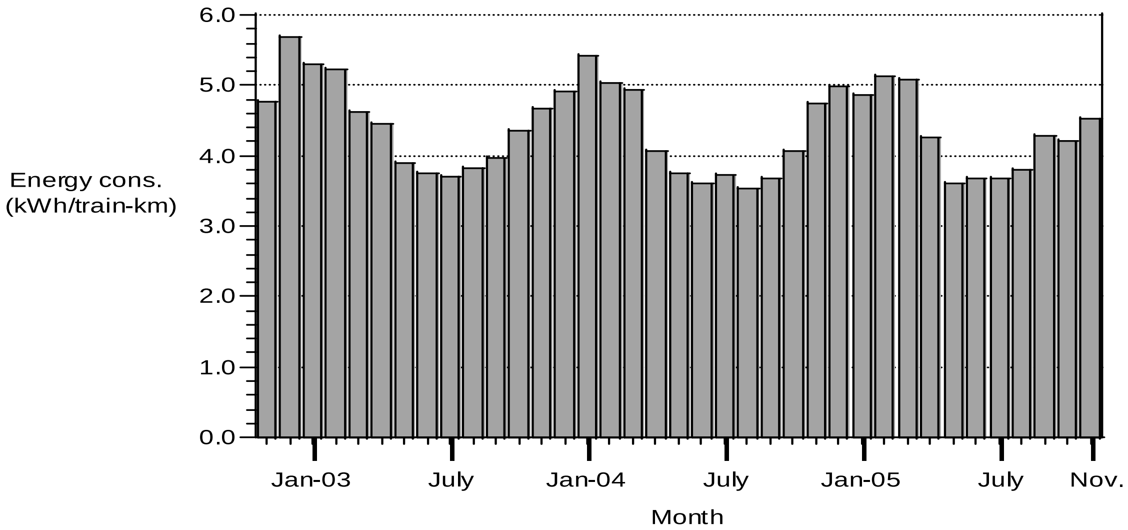

Fig 2-1 Energy consumption for a fleet of six Regina trains during three years.
Regional train service at X-Trafik in middle part of Sweden.
Monthly averages. Energy for parking on stabling tracks is included.

Electric energy as measured from the train's pantograph, i.e. losses in supply system is not included.

On some trains reported in this study the energy measurements are performed during a much shorter period than a year. The longer time series should allow corrections of measured energy data (under shorter periods) to an approximate yearly average, although such corrections are not actually made in this study. In doubtful cases the estimations are rather made towards the conservative side.

2.1.3 Load factor for different types of trains

In this study the load factor is defined as the ratio between the actual *number of passenger-km* in a specific train operation and the *number of offered seat-km*. The latter is proportional to the number of seats in the train.

The actual load factor varies largely on different trains in the course of the traffic day, week or year. The number of passengers also varies on different sections along the line; usually the load factor increases when the train is running through the more populated areas.

Trains in big city areas, serving passengers travelling for work or schools have usually very pronounced peaks in the number of passengers during rush hours (07 – 09 and 16 – 18). The number of passengers during the most dominant rush hour may be up to 5 - 6 times higher than the average during the whole traffic day (06 – 24). Such trains are usually called *local trains* or *commuter trains*, on intermediate distances also *regional trains*. A special type of local or regional trains is *airport trains*, serving airline passengers and airport staff. It is usually impossible – or very difficult – to even out the peaks over the day. The passengers have to travel when they need to, and the cost of travel is usually quite modest in relation to the benefits of being on work or schools on due time.

The large peaks in rush hours necessitate larger trains (with more seats or standing areas) than otherwise needed. Such trains are therefore running with a considerable spare capacity most of the day or year. The average load factor is usually quite modest – usually in the range of 20 – 40 %.

On the contrary, long-distance trains are different. Travel times are longer and are being spread out over a longer period of the day. Also, the cost of travelling long-distance is considerable for most passengers. Therefore, in order to push passengers to use empty seats on non-peak hours, ticket fares are usually lower on these hours. These factors result in a more spread-out travelling, with a higher and more even load factor over the day or the week. Modern high-speed trains - with competitive travel time and ticket pricing - usually have average load factors of 50 – 75 %, comparable with most domestic air lines. Slower conventional long-distance trains have usually a more modest load factor.

2.1.4 Load factor and energy consumption

In order to understand the importance of the load factor for the energy consumption we will at first discuss energy consumption of trains generally.

Energy consumption for train operations may be measured and expressed per ton-km, train-km, car-km, seat-km or per passenger-km. In the latter case the energy consumption is related to the number of passengers using the actual train or *to the number of passenger-km produced*. From an energy efficiency point of view, the latter is the most interesting.

The energy consumption of passenger trains have usually two dominating factors, namely the energy consumed for compensating the *air drag* and the energy consumed for *acceleration* of the train to the cruising speed. Besides these factors also the *rolling resistance* (sometimes called mechanical resistance) have some influence, as also energy for *comfort* (heating, illumination, carbody tilt, catering and others).

All equipment utilising energy on the train has *energy losses.* This means that not all consumed energy is converted into the desired effect, but instead into useless heat. Part of the losses are related to the auxiliary equipment such as ventilation and cooling of propulsion equipment, supply of compressed air for brakes, etc. The losses and auxiliaries usually consumes in the order of 20 – 25 % of the energy intake, as an average in modern trains. In the most efficient operating mode the losses may be somewhat lower than indicated above; however at lower levels of propulsion output (i.e. at almost idling) the losses are usually higher as a percentage.

By acceleration the train mass is given a higher speed. Electric energy is converted to kinetic energy. A higher target speed and train mass need more energy for acceleration. Thus, more passengers on the train will principally result in higher energy consumption. This is most important for trains with frequent stops and subsequent accelerations to high speed.

The additional energy consumption as an effect of increased train mass for additional passengers is, however, very small. For example, a three-car *Regina* train in fast regional operation (see Fig 1-2) with fully seated load (272 passengers, around 22 tonnes) has approximately 5 % higher energy consumption than an empty train. Another example is the *X 2000* high-speed train (Fig 1-1). Loaded with the maximum number of seated passengers (320 passengers, around 26 tonnes) the energy consumption of *X 2000* is estimated to increase in the order of 3 %.

From these figures it is easy to understand that the energy consumption for a train is quite constant and almost independent of the actual number of passengers, i.e. independent of the load factor. Thus, *per passenger or passenger-km the energy consumption is approximately inversely proportional to the actual load factor.* For example, a load factor of 60 % instead of 30 %, gives approximately half the energy consumption as measured per passenger-km.

In this study we throughout apply this simplifying assumption. Within the actual range of load factors (20 – 60 %) the resulting error would be only 1 – 2 %. Further, in most cases in the present study energy consumption (per train-km) is measured at about the actual average load factor, a fact that will reduce the error to almost zero.

2.2 Power supply for electric railways

Electric power for rail traffic in Denmark, Norway and Sweden derives from the national power grid. Conversion of electric power (between different voltages and sometimes also frequency of the alternating current) takes place in a number of stages as described in Sections 2.2.1 and 2.2.2 below.

2.2.1 Feeding stations and catenary

We will take the Swedish electrical supply system as a basis for the description of the Scandinavian systems. In *Sweden* electric power is usually fed to the railway from the public power grid in the form of high-voltage three-phase alternating current (130 kV, 50 Hz). This power is brought into Banverket's (the Swedish National Rail Administration) supply stations; see Figure 2-2. In these stations the electric power is immediately divided into two parts as described below.

The major part is taken to static converters (to some extent still also the older rotary converters) where the electric power is converted to a low-frequency single-phase alternating current (15 kV at 16 2/3 Hz) to be used by the trains. In order to feed the trains from the converter stations a so-called catenary cable is suspended over the track at a height of 5 – 6 m. On lines with heavy traffic and needs for a high amount of power over long distances, a supplementary high-voltage supply line (130 kV) is used, feeding power to the catenary via transformers. The extra high-voltage supply line reduces the voltage drop and the energy losses in the supply system. The low-frequency supply system also comprises socket terminals (1 kV) for stationary vehicle heating at stabling tracks.

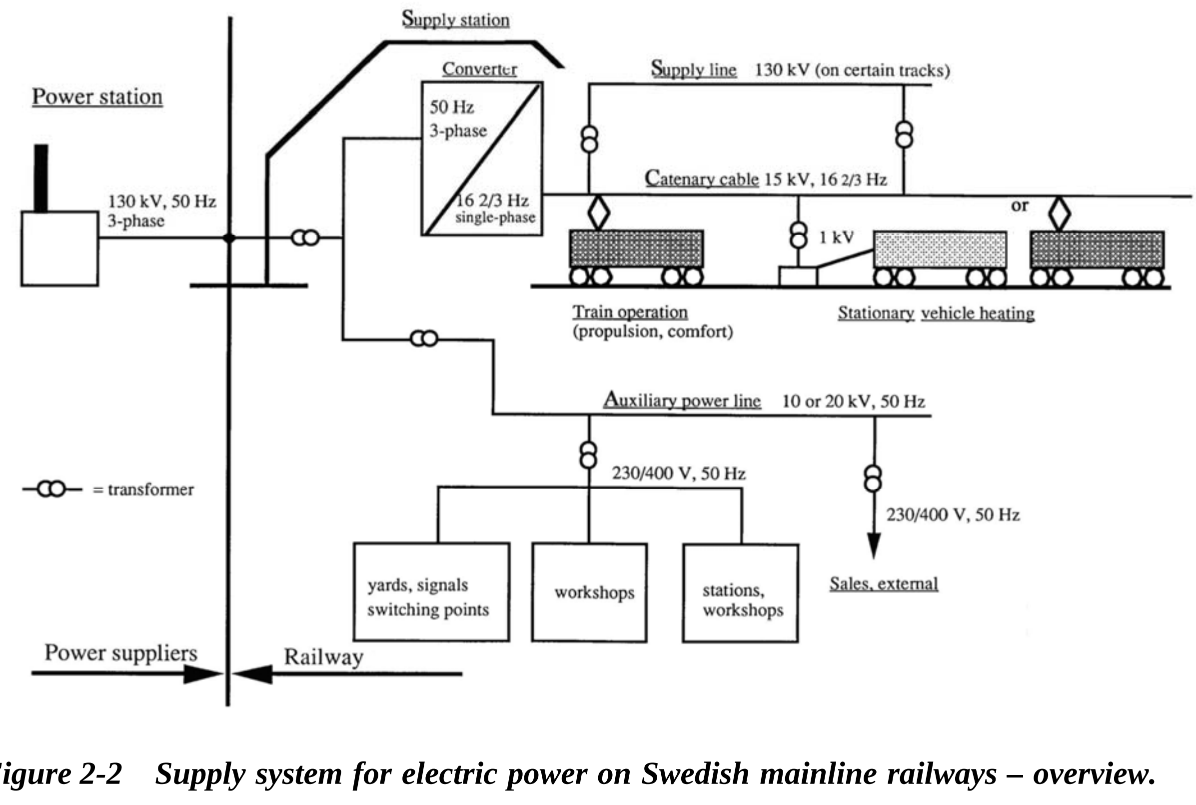

Figure 2-2 Supply system for electric power on Swedish mainline railways – overview.

The second and minor part is taken to an auxiliary power line feeding the railway's fixed installations, workshops, some railway stations, etc. The auxiliary power is finally converted to normal industrial standard, i.e. a three-phase alternating current at 230/400 V, 50 Hz. In the previously mentioned study of 1994 [1] the auxiliary electric energy (measured in GWh) was estimated to about 15 % of the total electric power intake.

In *Norway* the supply system is similar to the Swedish system, i.e. electric power is taken from the public electrical grid and is converted to single-phase alternating current of 15 kV, 16 2/3 Hz. Some differences exist, however being of minor importance for this study.

The supply systems in Sweden and Norway date back to the early 1900's at which time the locomotives required a low-frequent current (15 or 16 2/3 Hz), due to their principal technical design and features at that time. Thus, the somewhat complicated supply system in Sweden and Norway (as well as in Germany, Austria and Switzerland) has historical technical reasons.

In *Denmark* the electric supply system for the mainline railways is different from Sweden and Norway. The mainline railway electrification started in the 1980's, at which time it was feasible to have a supply system according to the normal industrial standard of 50 Hz. Such a system requires (somewhat simplified) only transformers between the public electrical grid and the catenary, i.e. the special frequency converter is not needed. The voltage is 25 kV according to modern international standards for railway mainline electrification. This system is simpler and less expensive and more efficient with less energy loss than in the older systems in Sweden and Norway.

Although the description of the supply systems is simplified it reviews the most important parts and features of interest to the present study.

2.2.2 Losses and energy efficiency

Energy consumption of trains is usually primarily measured (or calculated) at the pantograph level, i.e. at the intake to the train. However, the energy needed at the train's pantograph causes energy losses in the supply system. In order to estimate the energy being consumed in the railway system as a result of a specific train operation, these losses should be added to the energy intake to the trains. The losses in the supply system are dependent on the power load, which varies over time. In this study, however, we will estimate and consider the *average* losses in the system.

If the utilised energy is E (at the pantograph)
and the energy intake is E_{in} the energy loss is $E_{loss} = E_{in} - E.$

The relative loss e_{loss} (of the intake) is determined by $e_{loss} = E_{loss} / E_{in}.$

The energy efficiency η is then determined by $\eta = E / E_{in}$

or $\eta = 1 - e_{loss}.$

Also, e_{loss} may be determined by $e_{loss} = 1 - \eta$

If the utilised energy is known to be E, the energy intake E_{in} is $E_{in} = E / \eta.$

Example: If the energy consumed at the train's pantograph is 1000 kWh and the average efficiency is 83 %, the energy intake $E_{in} = 1000 / 0.83 \approx 1200$ kWh.

The energy loss $E_{loss} = 1200 - 1000 = 200$ kWh, and the relative loss
$e_{loss} = 200 / 1200 \approx 0.17$, i.e. 17 % loss of the intake.

The energy intake is 20 % higher than the utilised energy.

In the Swedish and Norwegian systems both the converters (with necessary transformers) and the catenary generate losses. In the Danish supply system there are no converters at all, and a less number of transformers, all factors reducing the losses. The higher voltage (25 kV instead of 15 kV) means less current at a fixed power output, which also reduces losses.

Some of the Swedish and Norwegian converters are still rotary converters being tedious to start and phase-in to the electrical grid. Therefore these converters are running quite a lot idling while producing idling losses. The average efficiency of these converters is therefore lower than the more modern static converters, being easier to start-up.

There are energy losses also in the catenary system. Losses in the catenary increase with an increased amount of current.

Efficiency and losses in the actual supply systems

The exact efficiency of the whole supply system, including converters, transformers, catenary and other parts is actually not exactly known. In *Sweden* Banverket has recently measured the efficiency of the *converter stations* for part of one year (Jan – August 2004) [24]. The average ratio between supplied energy to the catenary system and the energy intake from the public grid (excluding auxiliary power) was 0.915. This means that the average efficiency of the converter stations was 91.5 % during that time period. This is actually some 3 - 4 % better than in 1994 [1], likely due to a change from rotary to static converters.

No recent measurements or estimations on the efficiency of the Swedish *catenary* system are known according to Banverket. In 1994 [1] the average energy efficiency of the catenary system was estimated to 93 % for the older electric vehicles with thyristor control, consuming an increased amount of current for a fixed power intake. This is (technically) due to the out-of-phase current in relation to the phase of the voltage.

For the more modern vehicles, the current is essentially in-phase with the voltage, the consumed current and thus the losses are lower. Also the harmonics in the current are lower, also producing a less amount of losses. Modern electrically propelled rail vehicles have induction motor drives fed by advanced semiconductor converters. Practically all new electric trains delivered on the Scandinavian market since the early 1990's have these features. For this type of electric vehicles the average efficiency in the catenary system was estimated to 96 % in 1994.

For 2004 the same total efficiency is assumed for the Swedish catenary system. The traffic has increased from 1994 to 2004, in particular passenger services, to a minor extent also the rail freight transport. The higher power transferred should increase the percentage losses in catenaries, all other factors being equal. However, the supply system has been improved considerably during the 10 years. More 130 kV supply lines have been installed in parallel with the catenary, which should reduce the losses at higher power loadings. In all it is judged that the average efficiency of the catenary system should be approximately the same in 2004 as in 1994.

Total average efficiencies in the Swedish supply system (2004) are therefore estimated to

- $0.915 \cdot 0.96 \approx 0.88$, i.e. 88 %, for supply to modern electric trains, and
- $0.915 \cdot 0.93 \approx 0.85$, i.e. 85 %, for supply to the older types of trains.

These efficiencies are about 3 % better than in 1994. However, the overall average efficiency has improved by more than that, due to the larger amount of modern electric trains. A modern train of 2004 has about 6 % better efficiency (7 % less losses) in the supply system than the older types of trains in 1994.

Estimations of losses and energy efficiency have been made also in Denmark and Norway. For electric mainline railways in *Denmark* the average efficiency is reported to 95 % [15].

For southern *Norway* the average losses are reported to 14 % of the intake [17], i.e. the efficiency is 86 %. This is an average, so modern trains may have a slightly higher efficiency. As no other figures are known we use the (likely) conservative figure as above.

Losses in the supply system are included in the energy estimations

As pointed out previously losses in the power supply system will be included in the energy consumption estimations as reported in the following Chapters 3, 4 and 5. The energy measured at the train pantograph level is multiplied with the following factors

- 1 / 0.88 ≈ 1.14 for Sweden,
- 1 / 0.95 ≈ 1.05 for Denmark and
- 1 / 0.86 ≈ 1.16 for southern Norway.

Comments

It could be discussed whether the above kind of estimation is comparable to the energy consumption usually reported for road vehicles using petrol or diesel fuel, or in the air transport system using kerosene. In the latter cases the losses in the "road" or "air" systems – for fuel transport and others – before the petrol reaches the fuel tank, are usually not included in the energy consumption estimations.

However, the losses in the railway supply system have no direct equivalent in the other transport systems. The power supply system is very well integrated into the total railway system. This may be an argument for inclusion of losses in the railway supply system. Another argument is that we would like to make a somewhat conservative estimate rather than an estimate on the low side.

Finally, most important from a scientific point of view is that it is declared what is included and what is not included, in order to be transparent for further evaluations and considerations.

2.2.3 Energy recovery

A train consumes energy when it is accelerating or running uphill. The train also consumes energy due to air drag, mechanical (rolling) resistance and comfort needs.

The energy consumed for pure acceleration is converted into *kinetic energy* of the train, with exception of the losses in the propulsion system (including the need for auxiliary power). The energy needed for running uphill is converted to *potential energy* of the train, with exception of losses.

The kinetic energy of the train can principally be converted to electric energy if the electric motors are switched over to electrical generators, thus also producing a torque being able to contribute to the braking effort of the train. The generated electric energy can be fed back to the catenary through the electric propulsion equipment of the train. Thus energy is regenerated and partly recovered. Also this 'reverse' process will be subject to energy losses. Despite the losses, if the braking is made entirely by the "electric" regenerative brakes (except at very low speeds) a modern electric train can regenerate and recover as much as 60 – 70 % of the energy input for accelerating the train. Principally the same applies to the uphill and downhill cases.

Energy needed to overcome the air drag and mechanical resistance is dissipative and can not be recovered at all. Energy for providing a comfortable environment in the train (heating & air condition, lighting, catering etc) can not even be recovered. Therefore, in total the percentage amount of energy recovery is usually much less than the 60 – 70 % as mentioned above. However, trains running at modest speeds (100 – 140 km/h) stopping at closely located stations, may have a considerable degree of energy recovery, in some cases up to 30 – 40 %.

In the regenerative braking mode the motors are working as generators and electric energy is fed back via the pantograph to the catenary. Normally this regenerated energy can be used by other trains on the line. If other trains are not capable of absorbing the regenerated amount of energy, the energy may be fed back to the public network if the converter station is technically equipped accordingly. In some supply stations this is possible. Some recovered energy may also be used to provide auxiliary power.

However, sometimes these possibilities are occasionally insufficient to absorb all regenerated energy. In such cases the voltage on the catenary will rise. When the voltage is rising too high the regeneration is stopped automatically and the braking effort is produced by the mechanical brakes or the magnetic brakes. Mechanical brakes are also used as a supplement to the electric regenerative brakes if more braking effort is occasionally needed than the electric brakes are able to produce. Whatever the actual case, the energy recovery, as measured at the pantograph level, will include and reflect all these positive and negative effects.

A great proportion of electrically powered axles in the train, and a large amount of propulsion power, increase the chances of a large degree of energy recovery.

To conclude, modern electric trains with a high amount of propulsion power, and a large proportion of powered axles, are able to recover a considerable amount of the gross energy consumption, without loosing too much of the braking effort in normal operation. Most of the recovered energy, being fed back to the catenary, can normally be utilised by other trains or for other purposes.

The net energy consumption, i.e. energy intake minus regenerated energy, can be reduced by 10 – 30 %, where the lower figure is typical for high-speed trains with few stops; the higher figure is more typical for modern stopping trains at fairly low speeds. The cases shown in the following Chapter 3 will present examples of energy regeneration and recovery. However, none of these cases is a stopping train at a fairly low speed.

2.3 The various modes of electric power production

Electric power (or energy) is e.g. a carrier of energy produced (or converted) in some kind of power station. Electric power can be produced from various sources of primary energy.

The Nordic countries (Denmark, Finland, Norway and Sweden) have a common market for electric energy (Iceland is in this study not included in the common Nordic market for electric energy). Deficiency or surplus in one region or country is normally balanced by an exchange of electric energy through the high-voltage transmission grid connecting the different regions.

On the Nordic market a number of production modes are used. The different modes are used to varying extent from year to year, depending mainly on the availability of hydropower and closure of nuclear power stations. Therefore an average over a longer period should be estimated. In this study a 5 year period (2000-2004) is judged as being representative for the present electric power production.

Table 2-2 below lists the quantities of electric energy as produced with various modes, as an average over the years 2000 - 2004. As no summary is known, statistics from different sources [2, 3, 4, 5, 6, 7] are being used and summarized.

Table 2-2: Electric power production on the common Nordic market, Year average 2000 – 2004.

Average el. generation year: 2000-04	(TWh)	(%)
Total generation	377	100
Nuclear power	86	23
Thermal power	85	23
- condensing power	*29*	*8*
- CHP[1], district heating	*36*	*10*
- CHP[1], industry	*20*	*5*
- gas turbines, etc.	*0*	*0*
Hydropower	200	53
Other renewable power	6	2
- wind power	*6*	*2*

1) CHP = Combined Heat and Power Generation.

Comments

Between year 2000 and 2003 wind power is accounted for as ‘’other renewable power’’ in the statistics [2]. Power produced by waste and peat is accounted for as ‘’other thermal power’’. However, in year 2004 peat and waste is accounted for as “other renewable power” [2]. For the consistency of Table 2-2, power produced by peat and waste during 2004 is here accounted for as “other thermal power” as well. When considering the average emissions in years 2000 – 2004 the waste and peat are treated as renewable energy sources.

Existing condensing power stations have efficiencies in the range of 33 – 47 % [8, 9, 10], the most modern having about 47 %. This means that 53 - 67 % of the energy content become energy losses (low temperature heat). The combined gas cycle (gas turbines + steam turbines) is a modern mean of electric power production from fossil or other fuels, having an efficiency of 50 – 58 %. With combined electric and heat production (CHP) a total energy efficiency of 75 – 92 % can be reached [8, 9, 10].

The total amount of electric power generation is split between the different Nordic countries according to Table 2-3. Iceland is excluded in this study, since it is not connected to the Nordic grid connecting the other countries.

Table 2-3: Electric power production in the Nordic countries, year average 2000 – 2004.

	El. gen. (TWh)	El. gen. (%)
Denmark	38	10
Finland	75	20
Norway	123	33
Sweden	142	38
Total	377	100

In Sweden hydro and nuclear power is dominant. In Norway hydropower alone contributes to 99 % of the production. In Denmark coal-, oil- and gas-burning power stations produce about 3/4 of the country's electric power and about 7 % of the Nordic power. Finland has a more diversified production with almost 50 % being nuclear and coal, but also considerable amounts from hydropower, bio fuels, natural gas and peat. Regarding CO_2 emissions Denmark has the highest contribution on the Nordic electric power market, followed by Finland.

2.4 Average, marginal or "green" electric power?

There are a number of different opinions on how electric power (or energy) for rail operations – and its related air pollutions - for rail operations should be assessed and compared with other means of transport mainly using fossil fuels, mostly oil and sometimes natural gas.

In most railway systems there are no electric power stations exclusively dedicated for the railway operations, although such systems exist. Instead, the electric energy is taken from the public electrical grid, normally from the high-voltage system (for example 130 kV in Sweden). In the public electric grid there is a large number of different types of power stations supplying the electric energy; see for example Section 2.3. These different production means have very different characteristics regarding energy efficiency, emissions of air pollution etc.

As a matter of fact, one of the advantages with the use of electric energy is that it can be produced by a number of different means, the "best" of them could be chosen. For example, it is not necessary to produce electric power by burning fossil fuels with its related emissions of greenhouse gases (CO_2, NO_x) and other emissions. In the long term it is possible to use hydro, wind, solar, bio or nuclear power, at every time using the mode of electric power production that is considered to be the best from a number of considerations such as reliability of supply, economics and environmental performance.

In practice, in a public electric grid there is usually a mixed electric power production. The issue here is how to determine a comparable measure of energy consumption and air pollutant emissions in such a mixed system. This issue has been discussed by many authors; see for example [23]. There are at least three possibilities, according to Sections 2.4.1 – 2.4.3 below.

2.4.1 Average electric power production, with average emissions

This principle can be applied on a limited common market with a high amount of trading and exchange, in order to even out the deficiencies and surplus of electric energy between different regions and users at every time. The common Nordic electric power market fulfils these criteria.

This principle will be applied as one alternative in the estimations and conclusions in the following Chapters 3 – 5.

2.4.2 Marginal electric energy

Marginal electric energy is the energy being produced for an additional rail passenger or an additional train, or for an increased amount of rail transport, or a certain amount of rail transport instead of no rail transport at all.

In principal it is easy to understand the rationales behind such an approach. However, in practice it has not always been easy to determine the "marginal" energy and its related "marginal" emissions. The result depends on what production means being available when the demand for electric power increases. It also depends on the available transmission capacity. These factors vary over time. The result is also depending on the regulatory framework and other restrictions.

The result is also dependent very much on the timeframe in which the additional rail transport is carried out. We will consider two principally different timeframes as described below.

Short-term

This is the case where an additional passenger travels in one of the trains being run within a timetable period, being planned and decided by the train operator about a year before the real travel occurs. This passenger uses an otherwise empty seat. The additional "marginal" energy consumption related to this additional passenger - or a limited number of passengers using a fixed number of trains - is very small or negligible. For example, according to an estimation made in this study, an additional passenger travelling in an electric train from Stockholm to Gothenburg (455 km) would cause an additional energy amount in the order of 0.5 kWh (taken from the public electrical grid), or about 0.001 kWh per km. This corresponds to the energy content in about 0.05 litres of petrol or diesel fuel, for the 455 km additional journey. This marginal energy is very small, c.f. for example Chapter 4 in this report.

The very small amount of "marginal" energy for a single passenger is thus very small – practically negligible. Such a marginal contribution is very relevant for travel and travel decisions on an individual basis within a short timeframe (a year or less). However, such marginal effects will not be considered in the following chapters 3 -5, although this issue may be highly relevant for the individual potential passenger in the choice between different transport modes. Instead more long-term effects will be taken into account, being of interest for the planning of the future transport system.

Intermediate or long-term

Larger long-term variations in rail transport would cause an increased number of trains on the existing or extended rail infrastructure. If these trains will consume more electric energy than the existing trains, thus a "marginal" or additional amount of energy will be needed. An interesting issue is what amount of additional emissions of air pollutions that will result from the additional electric energy production.

Since 2005 onwards a regulatory framework – the EU *Emissions Trading Scheme* (ETS) - is in effect within Europe [11]. It is aimed to reduce greenhouse gas emissions according to the Kyoto obligations, by allocating gradually reduced emission allowances to different sectors and entities. If one entity is not able to reduce its emissions, or wants to even increase them, that entity must buy allowances from another entity being able to reduce emissions at a cost less than the price of the transferred allowances.

During the initial phase (2005 - 2007) only emissions of CO_2 will be regulated and subject to trading. It will cover large emitters in the power and heat generation sectors and in energy-intensive industries. Electric power generation is subject to this regulation and emission trading. In the second phase the scheme may be extended to other sectors (such the transport sector using fossil fuels) and to other greenhouse gases (NO_x, methane and others) also being part of the obligations in the Kyoto protocol.

As a result this regulatory scheme will limit the emission of greenhouse gases in the sectors being subject to the regulation. This means, for example, that any increase in electric energy demand will either force the electric power companies to make improvements in their power stations, or to build new ''green power'' production facilities, in order to reduce their specific emissions, or force them to buy allowances from other companies being able and willing to make the necessary improvements. This is under the likely assumption that most of the available allowances are utilised, i.e. the emissions are close to the allowed limit. *Hence the marginal contribution of CO_2 resulting from an additional need for electric energy will be zero.*

No study has been found on the expected marginal contribution of other pollutant emissions than CO_2. This is to be evaluated when experience from the EU trading scheme is gathered. However, the authors to this report find it most likely that also other emissions will be reduced considerably, due to the transition from burning fossil fuels to other technologies. An increased need for electric energy will likely speed up this process. In particular this will be the case if also other greenhouse gases will be regulated in later stages. *The authors to this report propose the hypothesis that the future marginal contribution of* NO_x*, HC and CO will be close to zero.*

2.4.3 "Green" electric energy

This is principally electric energy originating from renewable energy sources, e.g. existing hydro power, wind and solar energy as well as different bio fuels, the latter being fuels that will not contribute to the net emission of greenhouse gases.

In Sweden there is a trade system for "green" electric energy, the prices being somewhat higher than on the ordinary electric power market. It can be argued that the same mix of electric energy is produced anyhow, as long as "the market" is willing to buy and use the "non-green" energy. However, it can also be argued that the normally higher prices on the "green" segment in the long term will initiate an increased amount of "green" electric energy, due to new ''green power'' production facilities being built. In any case, on a "free" market it would be possible to contract energy from a specific sort of "green" electric power stations to be built on behalf of the energy users.

The latter arguments supports the opinion that a user being willing to pay a higher energy price for the higher level of future environmental development, also should be credited in terms of better environmental properties for the "green" energy.

2.4.4 Conclusions

From the above-mentioned facts and discussion, there is no obviously correct way to determine the amount of pollutant emissions into the air, related to a mixed production of electric energy (or power) in a public electrical grid. The result will be very dependent of whether short-, medium- or long-term marginal contributions are considered. It is also dependent on the regulatory framework for energy and emissions.

For this study we have decided to use three alternative evaluations. The first is the *average emissions from electric power generation on the common Nordic market* (Denmark, Finland, Norway and Sweden), according to data from 2000 – 2004.

The second alternative is the above-mentioned marginal contribution seen in a European perspective. Only carbon dioxide (CO_2) can be accounted at the current stage, as only CO_2 emission is currently regulated. The marginal CO_2 contribution in this perspective will principally be zero from year 2005 onwards. The authors to this report find it very likely that also other marginal emissions will be close to zero.

The third alternative is average "green" electricity, i.e. electric energy produced from renewable sources.

In the present study there is no choice or discussion on whether one or the other method should be preferred. All of them could be motivated depending on the circumstances and the context in which the demand for electric power is to be met.

2.5 Emissions from electric power production

2.5.1 Average on Nordic market

The average emissions of air pollutants on the common Nordic market for electrical power during 2000 - 2004 were estimated from sources according to Section 2.3. The result is shown in Table 2-4 below.

Table 2-4: Air pollutions as an average (years 2000-2004) for electric power on the Nordic market.

Carbon dioxide	(CO_2)	96 g/kWh $_{el}$
Nitric oxides	(NO_x)	208 mg/kWh $_{el}$
Hydrocarbons	(HC)	1 mg/ kWh $_{el}$
Carbon monoxide	(CO)	14 mg/kWh $_{el}$

The emissions above include an addition of 4 %, being the upper limit of estimated losses in the high-voltage electric power transmission from the power stations to the inlet of the railway's converter station. Thus the above listed emissions refer to the amount of electric energy as supplied from the public high-voltage grid (130 kV) to the inlet of the railway's converter stations.

As mentioned earlier in Section 2.2 the electric energy consumption for different train services will be determined as the energy as supplied from the public grid to the inlet of the converter stations of the railways. Thus average losses in converter stations and in the overhead catenary are added to the measured energy at the train's pantograph. The emissions should therefore refer to the amount of energy at the inlet from the public grid.

2.5.2 Marginal effects

As discussed and motivated in Section 2.4.2 the marginal emission of CO_2 will be zero, seen in a European perspective where the EU emission-trading scheme is applied. Also other marginal emissions (NO_x etc) are set to zero, as motivated in the previous Section 2.4. In any case, the short-term marginal contribution - within a timetable period – is close to zero.

2.5.3 "Green" electric energy

Based on estimations made by the Swedish electric power company *Vattenfall* for the year 1996 [12] the "Green" electric power from renewable energy sources – in this case hydropower - has emissions according to Table 2-5 below.

Table 2-5: Estimated emissions of air pollutants for ´Vattenfall´ Swedish hydropower.

Carbon dioxide	(CO_2)	0.07 g/kWh $_{el}$
Nitric oxides	(NO_x)	0.27 mg/kWh $_{el}$
Hydrocarbons	(HC)	0.26 mg/ kWh $_{el}$
Carbon monoxide	(CO)	1.9 mg/kWh $_{el}$

The emissions are related to the continuous operations of the hydropower stations, while emissions during the construction phase or reinvestments in machinery are not included. The level of the above estimations regarding CO_2 and NO_x is confirmed by a more recent Environmental Product Declaration (EPD) made in 2005 regarding *Vattenfall's* Nordic hydropower [13]. As a matter of fact, the emissions related to continuous operations are slightly lower in the EPD document than in the estimations for 1996.

In the EPD document [13] also the total life-cycle emissions – including the construction and reinvestment phases - are being estimated. Thus the life-cycle CO_2 emissions are estimated to 4.4 g per kWh electricity delivered at the inlet to the railway's converter station. The life-cycle NO_x emissions are estimated to 4.0 mg per delivered kWh. This is just a few percent of the average emissions on the common Nordic market.

Even if also these life-cycle emissions are very low (compared to emissions from electric power generation by fossil fuels), it is decided not to use them for the further estimations in this study. The reason is that life-cycle emissions are not comparable with the estimated exhaust emissions from other means of transport, i.e., road vehicles and airplanes, using liquid fossil fuels. In the latter cases the life-cycle emissions due to construction and operations of liquid fuel production facilities are usually not included.

2.6 Summary of what is included in this study

As a result of the facts and discussions in Sections 2.1 – 2.4 the energy consumption and the related air pollution are determined as follows:

- Energy as used for *propulsion* and *comfort* during the journey, determined as a sample of representative types of rail services. Energy consumed at *idling* outside scheduled operations is also included, as is also energy used for *catering* provided onboard the trains, where applicable.
- *Electrical energy* (or power) as supplied *from the public high-voltage electrical grid* to the inlet of the converter station of the railway. Thus losses in converter stations and overhead catenary are added to the energy as measured at the train's pantograph (current collector) level.
- Air pollution related to electric propulsion, as an *average* from electric energy production within the common *Nordic market*, in the years 2000 – 2004.

  Alternative measures of air pollution are also estimated. One alternative is the marginal contributions in an all-European perspective applying the EU Emissions Trading Scheme. Another alternative evaluation - the so-called "Green electric energy" - is also made.

Thus, the determined energy consumption and air pollution in the present study does not include energy related to stationary vehicle heating (parking), workshop treatment or any effect on infrastructure construction, operation or maintenance. This should be comparable to most estimations for other modes of transport using fossil fuels (petrol, diesel oil, aircraft fuels etc).

3 Energy consumption and air pollution from modern trains

3.1 Methodology and definitions

The exact methodology for assessing the energy consumption of the different trains is dependent on the data being available or being possible to collect for each different case. In all cases energy measurements have been made as the basis for energy assessment. For all the trains except *X 2000* the energy was measured during regular commercial service with the train's ordinary energy meter that was sampled at various intervals. This equipment has an accuracy and reliability allowing it to be used as a basis for charging of energy consumption from the Swedish National Rail Administration (Banverket). For the Norwegian trains (Flytoget, Signatur) the energy meters are verified for energy charging by DNV (Det Norske Veritas).

In three cases measurements have been made over at least a full year, thus the operational conditions include seasonal variations in weather conditions. If not, with one exception the measurements are performed during a period where the energy consumption is estimated to be approximately representative for an average over a year. Normally the energy consumption is at a maximum in Jan - Feb, while it is at a minimum during May - September. For the Norwegian train Signatur, measurements where made during winter conditions (Jan 20 – Feb 7, 2003) that is further discussed in Section 3.6.

In one case (*X 2000*), older measured data (from a number of energy measurements in commercial service during 1994 [1]) have been used for verification and calibration only, as the old measured data were not consistent with the prevailing conditions for the actual train operations. For different reasons it was not possible to collect new energy data. Therefore simulations for old and actual operational conditions has been made, thus the simulations have been validated and calibrated by comparison with old measured data.

Assessment of a train's energy consumption has generally been performed according to the following steps:

1. Energy consumption of the train is measured close to the energy intake, i.e. close to the *pantograph* (the current collector) where the electric energy is taken from the overhead contact cable, more often called *catenary.* The regenerated energy from braking and downhill grades is subtracted from the intake. The remaining energy is the *net energy consumption at the pantograph level.*
2. From these figures the estimated *energy intake for stationary heating and air condition at parking* on stabling tracks is subtracted from the net energy consumption, in cases where such energy is included (more or less) in the measured and sampled energy consumption data.
3. The estimated *energy for idling outside scheduled service* - for example at end stations before the train departs or after the train arrival to its final destination – is added to the measured energy if not included in the measured data.
4. The measured and corrected energy, as above, is approximately converted to the *energy intake from the public electrical grid,* by adding average losses in catenaries and converter stations. This figure is converted into *specific energy consumption from the public grid, as an average (kWh) per train-km.*
5. Knowing the average passenger load for the specific type of train operation, the *specific average energy consumption (kWh) per passenger-km is determined.* Usually the average passenger load is calculated from the so-called *load factor*, i.e. the total number

of passenger-km divided by the total number of seat-km run by the actual train service, as reported by the train operator. By taking the passenger load into consideration the outcome of this exercise will not only depend on the technical and operational characteristics of the train, but also on other factors of organisational or socio-economic origin.

6. The *specific pollutant emissions* attributed to the train operation in question, is determined as the specific energy consumption according to point 5 above, times the *specific emission per unit (kWh) of electricity* as taken from the high-voltage electrical grid. The electric power production is on average about 4 % higher than the intake from the electrical grid, because of losses in the high-voltage grid. A 4 % addition is included also in the specific emissions. The specific emissions are largely dependent on the electric energy production, as earlier discussed in Sections 2.2 – 2.4.

3.2 High-speed train X 2000

The Swedish high-speed train *X 2000* is used for premium long-distance services between major cities in southern and middle Sweden. *X 2000* trains mainly provide services on the lines Stockholm - Göteborg (Gothenburg) (455 km), Stockholm – Malmö – København (Copenhagen) (661 km), Stockholm – Sundsvall (402 km) and Göteborg – Malmö (306 km). Speeds are usually 180 – 200 km/h on these lines, although minor parts are run at lower speeds.

For the Swedish high-speed train *X 2000* the energy consumption in actual services is determined by a step-by-step procedure as described below:

a. The energy consumption as determined on the line Stockholm – Göteborg in 1994 [1] is used as a basis. A train consisting of one power unit, four intermediate trailers and one driving trailer, made four return trips, half of them in February and half of them in May. The average of these should be close to the annual average. Energy measurements were made at the pantograph (current collector) level. The energy intake was 5209 kWh as an average, while the energy recovery was 620 kWh, resulting in a net energy of 4589 kWh.

   This energy consumption was converted to the amount of energy supplied from the public electrical grid, thus adding the losses in converter stations (12 % of inlet, as determined in 1994) and catenary (4 %). The resulting energy consumption taken from the power grid was determined to 5414 kWh, for an average run between Stockholm and Göteborg in 1994. This makes 11.87 kWh per train-km. The recovered energy is around 12 % of the intake.

   In 1994 only dedicated 1st class *X 2000* trains were in regular service at SJ. The specific energy consumption per passenger-km in a prospective mixed 1st and 2nd class service was determined by assuming the same average load factor (44 %) as in SJ InterCity services of 1994, applied to a prospective mixed-class train with 270 seats. The resulting specific energy consumption was calculated to 0.100 kWh per passenger-km. Corrected for idling outside scheduled service – but exclusive stationary heating at stabling tracks - this makes 0.103 kWh per passenger-km.

b. Since 1994 the *X 2000* services on the line Stockholm – Göteborg have been subject to a number of changes. In 2004 the situation was as follows: (1) The line and its stations is upgraded, resulting in less speed restrictions; also the line is slightly shortened; (2) The average number of underway scheduled stops are four instead of two; (3) The *X 2000* trains on this line consist of one additional trailer car, i.e. there are six trailers (including the driving trailer) instead of five, resulting in 320 seats instead of 270; (4) The average load factor is (2004) approximately 55 % instead of the tentatively assumed 44 % in 1994.

c. For the present study the energy consumption of 1994 was firstly simulated, as a reference case and as "calibration" and validation against measured data. Secondly the new *X 2000* service of year 2004, according to point b. above, was simulated. This makes 5315 kWh for an average run [20].

   This amount of energy is converted to the energy supplied from the public electrical grid, thus adding the average losses in converter stations in 2004 (8.5 % of inlet) and catenary (4 % of the outlet from converters). The resulting energy consumption taken from the power grid is determined to 6050 kWh, for an average run between Stockholm and Göteborg, i.e. 11.7 % higher than in 1994. This makes 13.30 kWh per train-km, i.e. about 12 % higher than in 1994. Compensated for idling outside scheduled service this makes 13.6 kWh per train-km.

   However, the *X 2000* trains nowadays convey more passengers than in 1994, as an average, partly due to longer trains, partly because of a higher load factor than anticipated in 1994. The load factor for these long distance trains – as an average over the last years up till 2004 – is in the order of 55 % instead of 44 %. With the higher load factor, i.e. 176 passengers in a 320-seat train, the resulting specific energy consumption is calculated to 0.075 kWh per passenger-km. Corrected for idling outside scheduled service this makes:

Specific energy for typical X 2000 high-speed service: 0.077 kWh per passenger-km.

This is 25 % less than the earlier (in 1994) estimated energy consumption of *X 2000* for a mixed 1st and 2nd class version (30 % 1st class and half a bistro car).

The energy consumption supplied from the power grid is basis for determination of:

Specific air pollution			***Nordic average***	***Marginal***	***Green energy***
- Carbon dioxide	(CO_2)	g /pass-km	7	0	0.006
- Nitric oxides	(NO_x)	mg /pass-km	16	≈0	0.021
- Hydrocarbons	(HC)	mg /pass-km	0.08	≈0	0.020
- Carbon monoxide	(CO)	mg /pass-km	1.1	≈0	0.15

It was originally planned to verify the above estimated energy consumption by measurements on one or two *X 2000* trains in regular service at SJ AB. Due to delays in the delivery of equipment for energy measurement and data storage such verification has not been possible to perform within the time frame of the present study. However, experiences from previous simulations and verifications indicate that errors are most likely within a few percent of the estimations.

Note that an average load factor of 55 % is used is the estimations above, as being typical for the years 2002 - 2004. In 2005 a higher load factor of 60 % is reported for the *X 2000* services. Whether this improvement is occasional or steady is not known currently. If the higher load factor is taken into consideration the energy consumption – as well as the specific air pollution – per passenger-km would be some 8 % less than in the estimations above.

3.3 Fast regional trains of type ”Regina”

Energy consumption for Regina trains is recorded on a number of trains in two types of service A and B as described below.

Service type A is run in an a quite densely populated area including the Swedish capital Stockholm;

Service type B is run in an area with a more average or sparse Swedish population density; see below.

3.3.1 Regional service type A

The services called “Tåg i Mälardalen” (*TiM*) are connecting cities around lake Mälaren, including Stockholm, Västerås, Eskilstuna, Örebro, Uppsala and others. This is a fast regional service on intermediate distances (100-200 km), with scheduled stops at a distance of about 25 km as an average. The maximum permissible speed is 200 km/h at about 60 % of the lines, otherwise 120 – 160 km/h. Due to the quite high density of population there is a considerable amount of travelling in the region, with a concentration in morning and afternoon hours on workdays. These trains have had an average load factor of about 35 % for a number of years up till 2004.

Energy consumption has been measured on 10 train units in regular service, 5 units in 2-car consist and 5 units in 3-car consist [21]. The energy is measured at pantograph level with the internal energy meter on each train. The accumulated measured energy (in kWh) is read from the internal memory on a number of occasions, the first in November 2003 and the last in October 2004, i.e. over almost one year. Thus all seasons are covered: winter, spring, summer and autumn. Also the actual running distance (in km) is read from each train on the same occasions. The estimated energy for stationary heating and air condition at parking on stabling tracks (approx. 7 % of intake) is subtracted from the measured energy [14]. The extra energy consumption for non-scheduled idling is included.

From these data the average energy consumption per train kilometre is calculated. Measured energy at pantograph level is recalculated to energy as supplied from the public grid.

The average load factor is around 35 % as estimated by the operator *SJ AB*. Finally the specific energy per passenger-km is calculated as well as the related air pollutions from the electricity production according to a Nordic electrical power average.

	2-car trains	***3-car trains***
Total energy intake at pantograph (MWh) excluding energy for parking	6332	9549
Energy recovery at pantograph (MWh)	987 (16 %)	1640 (17 %)
Total net energy from public grid (MWh)	6085	9004
Total running distance (km)	1 028 817	1 083 547
Energy per train-km (kWh/km)	5.91	8.31
Number of seat-km x 10^6	171.8	294.7
Number of passenger-km x 10^6	60.1	103.2
Specific energy (from public grid) (kWh /pass-km)	0.101	0.087

Specific energy, for average type A fast regional service: 0.094 kWh per passenger-km

Specific air pollution			***Nordic average***	***Marginal***	***Green energy***
- Carbon dioxide	(CO_2)	g /pass-km	9	0	0.007
- Nitric oxides	(NO_x)	mg /pass-km	20	≈0	0.026
- Hydrocarbons	(HC)	mg /pass-km	0.1	≈0	0.025
- Carbon monoxide	(CO)	mg /pass-km	1.3	≈0	0.18

3.3.2 Regional service type B

This type of regional train service is exemplified by the trains serving the regions of Gävle and Uppsala, stretching some 70 – 300 km north of Stockholm. The first service is called "*X-Trafik*"; the latter is called "*Upptåget*". As in service type A this is also a fast regional service on intermediate distances (100-200 km). *X-Trafik* has scheduled stops at a distance of about 25 km as an average, while *Upptåget* stops at an average of 10 km. The maximum permissible speed is 180 km/h at about 50 % of these lines, otherwise mostly 120 – 160 km/h.

Energy consumption has been measured on 9 trains in regular service, all being 2-car units. The time period from the first to the last energy reading is from November 2002 to October 2005 for *X-Trafik* (6 trains) and from February to May 2004 for *Upptåget* (3 trains) [22]. Thus Upptåget is just measured for about 4 months during winter and spring, estimated as being some 2 % above a typical annual average, which is neglected in the evaluation. The energy is otherwise measured and evaluated under approximately the same conditions as for the service type A.

The average load factor is 20 % as estimated by *X-Trafik*. The same load factor is used for *Upptåget*, assumed to being a typical average for this type of passenger transport. Finally the specific energy per passenger-km is calculated as well as the related air pollutions from the electricity production according to a Nordic electrical power average.

	X-Trafik	***Upptåget***
Total energy intake at pantograph (MWh) excluding energy for parking	24 125	1 779
Energy recovery at pantograph (MWh)	5 021 (21 %)	411 (23 %)
Total net energy from public grid (MWh)	21 758	1 557
Total running distance (km)	4 379 953	249 124
Energy per train-km (kWh/km)	4.97	6.25
Number of seat-km x 10^6	731	41.6
Number of passenger-km x 10^6	146	8.3
Specific energy (from public grid) (kWh /pass-km)	0.149	0.187

Specific energy, for average type B regional service: 0.168 kWh per passenger-km

Specific air pollution			***Nordic average***	***Marginal***	***Green energy***
- Carbon dioxide	(CO_2)	g /pass-km	16	0	0.011
- Nitric oxides	(NO_x)	mg /pass-km	35	≈0	0.045
- Hydrocarbons	(HC)	mg /pass-km	0.17	≈0	0.043
- Carbon monoxide	(CO)	mg /pass-km	2.4	≈0	0.32

3.4 Øresundstoget (OTU)

Øresundstoget – also called the Øresund Train Units (*OTU*) – runs fast regional services over the Øresund link (including the bridge) between Sweden and Denmark. The Øresund region includes the Danish capital København (Copenhagen), and the Swedish third city Malmö, as well as a number of medium-sized other cities. Scheduled stopping distances are about 18 km in Sweden and 5 km in Denmark. Maximum speed is usually 140 - 180 km/h, but parts of some lines are more restricted. This is the case also over the most busy section between Copenhagen and Malmö, including the 8 km bridge over the sea straight of Øresund.

Due to the quite high density of population, as well as the fairly high charging for cars running over the Øresund bridge, there is a high amount of rail travel in this area. These fast regional trains have an average load factor of about 41 % as an average, as reported from the Danish main operator DSB [15]. Most trains are running in 6- or 9-car consists, although some are run as the minimum 3-car units.

Energy consumption has been measured by the operator DSB on 15 return trips of regular service between Copenhagen and Malmö (47 km) [15]. The energy is measured at pantograph level with the internal energy meter. Measurements were performed in January and April. Due to this procedure energy for stationary heating and air condition at parking on stabling tracks is *subtracted from* the measured energy. The extra energy consumption for non-scheduled idling is included.

The total measured net amount of energy (at pantograph level) is divided by the total amount of train-km for the measured train sets (3-car units). This makes an average of 6.1 kWh per train-km (3-car unit). The losses in catenary and feeding stations are reported to be 5 % in Denmark and 12 % in Sweden. Using the average loss - approximately 9 % of energy intake – the corresponding energy taken from the public grid is estimated to 6.7 kWh per 3-car train unit. As each 3-car unit has 237 seats and the load factor is 41 %, the following will apply:

Specific energy, Øresundstog: 0.069 kWh per passenger-km.

Specific air pollution			***Nordic average***	***Marginal***	***Green energy***
- Carbon dioxide	(CO_2)	g /pass-km	7	0	0.005
- Nitric oxides	(NO_x)	mg /pass-km	14	≈0	0.021
- Hydrocarbons	(HC)	mg /pass-km	0.07	≈0	0.020
- Carbon monoxide	(CO)	mg /pass-km	1.0	≈0	0.15

Comment: The energy measurements were performed during a limited number of regular return trips between Copenhagen and Malmö (47 km), i.e. just a part of the total operations for this type of train. However these (limited) operations are judged to constitute an approximate average from an energy consumption point of view. Speeds on this part of the line are representative for the total operations with the *OTU* trains and so are also the average scheduled stopping distances (9.4 km). The measurements are made in January and April, which should not be far from a year average, possibly a few percent higher.

The conclusion is that the energy estimation based on the above-mentioned DSB measurements is approximately representative for the total *OTU* operations. However, the deviations from the true average – i.e. the uncertainty - are possibly higher than for the previous *X 2000* and *Regina* cases, say up to ±10 % in the OTU case.

3.5 Type 71 ”Flytoget”

Flytoget – officially designated as *Type 71* - is a Norwegian dedicated high-speed airport shuttle train to and from the Gardermoen airport, serving the Oslo city (49 km) and the line to Asker on the other side of Oslo city (further 25 km away). Almost 50 % of the trains are non-stop trains between Oslo city and Gardermoen. These trains are scheduled to cover the distance of 49 km in 19 minutes. Maximum speed is 210 km/h on the new line between Oslo and Gardermoen, of which a considerable part is laid in tunnels. Speeds between Oslo and Asker are lower. Between Oslo and Asker there are 4 intermediate stops. Many trains also stop at Lillestrøm between Oslo and Gardermoen.

An independent state-owned company – *Flytoget AS* – operates the airport shuttles.

Energy consumption has been measured on all 16 train units in regular service during 2004 [16]. The energy is measured at pantograph level with the internal energy meter on each train. The accumulated measured energy (in kWh) is read from the internal memory at every turn of month, starting at Jan 1st and ending at Dec 31st. Thus all seasons are covered: winter, spring, summer and autumn. Also the actual running distance (in km) is read from each train on the same occasions.

The extra energy consumption for non-scheduled idling is included.

The total measured net amount of energy (at pantograph level, after energy recovery) is 42 004 MWh over 4.86 million km of 3-car unit train operation. This includes the energy for stationary heating and air condition at parking on stabling tracks, constituting 13 % of energy intake as estimated by Flytoget AS [16, 17]. If this amount is subtracted from the measured energy, an energy amount of 36 627 MWh remains as consumption for propulsion, comfort and non-scheduled idling.

The losses in catenary and feeding stations are about 14 % of intake as an average in southern Norway [17]. The energy intake from the public grid is then added up to 42 590 MWh in total during 2004. This makes an energy consumption of 8.76 kWh per train-km for propulsion, comfort and idling.

Each 3-car unit has 178 seats and the load factor is estimated to 27 % by Flytoget AS

Hence

Specific energy, Flytoget: 0.182 kWh per passenger-km.

Specific air pollution			***Nordic average***	***Marginal***	***Green energy***
- Carbon dioxide	(CO_2)	g /pass-km	18	0	0.013
- Nitric oxides	(NO_x)	mg /pass-km	38	≈0	0.049
- Hydrocarbons	(HC)	mg /pass-km	0.19	≈0	0.047
- Carbon monoxide	(CO)	mg /pass-km	2.6	≈0	0.35

3.6 Type 73 "Signatur"

Signatur – officially designated *Type 73* - is a long-distance train serving the electrified main lines in southern and middle Norway. The trains are mainly serving the main lines Oslo - Trondheim (553 km), Oslo – Bergen (489 km) and Oslo – Kristiansand – Stavanger (587 km). Generally these lines run in mountainous regions, they have partly considerable gradients and many curves, although parts of the lines are straighter. Maximum speed is 210 km/h, but *Signatur* operations are – despite the tilting carbody and its increased speed in curves - more typically run at speeds between 100 and 160 km/h due to frequent curves.

The Signatur trains are run by *NSB AS,* the main operator in Norway.

Energy consumption has been measured on all Signatur train units in regular service during the period Jan 20 – Feb 07, 2003 [19]. The trains were mostly run on the three main lines as mentioned above. The energy is measured at pantograph level with the internal energy meter on each train, figures on energy consumption and running distance taken by the drivers at each tour. These figures were recalculated into average net energy consumption per gross-ton-km, based on an assumed train weight of 224 tonnes. The net energy at pantograph level is summed up to 36.5 Wh per gross-ton-km or 8.17 kWh per train-km.

The extra energy consumption for non-scheduled idling is assumed to be included. The energy for stationary heating at parking is not included.

The losses in catenary and feeding stations are about 14 % of intake as an average in southern Norway [17, 18]. The energy intake from the public grid is then added up to 9.50 kWh per train-km for propulsion, comfort and idling.

Each 4-car unit has 201 seats (excluding bistro seats) and the load factor is 60 % as an average on the main lines according to NSB AS. This turns to an average number of 120 occupied seats per train unit. Hence

Specific energy, Signatur: 0.079 kWh per passenger-km.

Specific air pollution			***Nordic average***	***Marginal***	***Green energy***
- Carbon dioxide	(CO_2)	g /pass-km	8	0	0.005
- Nitric oxides	(NO_x)	mg /pass-km	16	≈0	0.021
- Hydrocarbons	(HC)	mg /pass-km	0.08	≈0	0.020
- Carbon monoxide	(CO)	mg /pass-km	1.1	≈0	0.15

Comment: The energy measurements were performed during a short period, less than 3 weeks, in January - February 2003. As shown earlier in Section 2.1.2 there are considerable seasonal variations in train's energy consumption. Swedish examples indicate some 10 - 15 % higher energy consumption for propulsion and comfort during January - February than the annual average. Thus a certain reduction in the measured figures for *Type 73 Signatur* should be justified in order to achieve a representative average. However, it is uncertain how much the energy figure should be reduced and it is also uncertain how actual conditions in Norway differ from the Swedish examples. Therefore no reduction is made. *The energy consumption for Type 73 Signatur, as stated above, should therefore be considered as a likely conservative estimation.* Due to this, and due to the limited number of energy measurements, the estimations for 'Signatur' are judged to have a possible error of 10 – 15 %.

4 Comparisons with older trains and other transport modes

4.1 Comparisons with older trains

In this study a number of modern fast passenger trains for long distance or regional passenger rail services are investigated with respect to energy consumption and its related emissions of pollutants into air. Compared to most of the older trains, investigated in the earlier mentioned report of 1994 [1], the speed has increased considerably and the travel time has been substantially reduced. Also the load factor has been changed to some extent. It is of interest to investigate how these changes have influenced the energy consumption and the related air pollutions per seat-km or per passenger-km. We will make two comparisons:

(1) The current *X 2000* operations (2004, 200 km/h) is compared with the loco-hauled *InterCity (IC)* trains of 1993/94, the latter having a top speed of 160 km/h.

(2) The current fast regional train *Regina* (2004, 200 km/h) is compared to the loco-hauled *InterRegional (IR)* trains of 1993/94, the latter having a top speed of 130 km/h.

4.1.1 Comparisons with current X 2000 services

For this comparison we will – as a typical example - use the high-speed services between Stockholm and Göteborg (Gothenburg) on a railway distance of 455 km. We will take the case of a mixed 1st and 2nd class train (having 25 - 30 % of the seats in 1st class) and half a 'Bistro' car. The high-speed train *X 2000* in the version used in 2004 will be compared with a loco-hauled *InterCity* train in 1993/94.

Based on the description in Section 3.2 and the previous report of 1994 [1], the comparisons can be summarised according to Table 4-1. Figures from 1994 are corrected to include the effects of non-scheduled idling, that was not included in the original estimations of 1994.

Table 4-1: Energy consumption and emissions of air pollutions for different generations of long-distance trains Stockholm - Göteborg (455 km). *LF = Load Factor*

	Energy *per seat-km* ***per pass-km***	***Average emissions per pass-km***		***Marginal/Green emissions per pass-km***	
	(kWh)	*CO_2 (g)*	*NO_x (mg)*	*CO_2 (g)*	*NO_x (mg)*
X 2000 (2004) 6 cars, LF 55 % of 320 seats	0.042 ***0.077***	7	16	0 / 0.006	0 / 0.021
Loco InterCity (1994) 8 cars, LF 44 % of 432 seats	0.048 ***0.108***	10*	22*	Not investigated	

*) Corrected for the Nordic common market for electric power.

Comments and conclusions: *X 2000* of 2004 has almost 30 % lower energy consumption per passenger-km than the typical loco-hauled *InterCity* train of 1994. This is partly due to the technical features of *X 2000*. Still more important is the improved load factor – from 44 to 55 % - being the result of a more attractive train and a more active pricing and yield management from the operators side (*SJ AB*). Still more efficient are the X 2000 services on this line in 2005, where an average load factor of 60 % is reported by *SJ AB*. This higher load factor would reduce the energy consumption (and the related emissions of air pollution) by a further 8 %.

The average air pollution has been estimated as the average on the common Nordic market for electrical power due to the transition from the Swedish electric power market (with mainly hydro- and nuclear power) to the common Nordic market containing also a certain amount of coal-fuelled electric power stations, in particular in Denmark. However, from 2005 onwards the marginal effects are principally zero, as the newly introduced EU emission trading scheme will limit the emissions from electric power production, principally independent of the actual electric power consumption.

4.1.2 Comparisons with current Regina regional train services

For this comparison we will – as a typical example - use the fast regional train services in Mälardalen, from Stockholm westwards to Västerås, Eskilstuna, Örebro and other medium-sized cities. A representative section in this regional rail system is Stockholm–Västerås, containing both high-speed sections (about 70 % allowing 200 km/h) and lower-speed sections. In 1994 most of the rail traffic between Stockholm and Västerås was carried out by loco-hauled trains, typically consisting of a four-axle electric locomotive (type *Rc*) hauling 3 - 7 cars, typically 4 cars. These older trains had a maximum speed of 130 km/h on about 2/3 of the line, otherwise lower.

In 2004 a large part of these operations are carried out by the wide-bodied *Regina* trains (see Figure 1-2), an EMU (Electric Multiple Unit) running in train consists of 2 - 5 cars, typically 3 cars.

Figure 4-1 A loco-hauled passenger train, being a typical train configuration on the Stockholm-Västerås line in 1994. (Source: SJK / T Lakmaker)

Max speed in service 130 km/h
Train mass in running order 261 tonnes

In 1994 energy consumption was measured on some 8-car loco-hauled trains, in top speeds of 130 and 160 km/h respectively. The energy consumption for these trains is reported in [1]. At a top speed of 130 km/h and an average stopping distance of 45 km the energy consumption was measured as an average of 17.9 kWh per train-km or 0.041 kWh per seat-km. With 35 % load factor this is 0.119 kWh per passenger-km. These figures relates to an average ambient temperature of -10 °C.

Approximately corrected for the actual average conditions on the Stockholm-Västerås line, i.e. a shorter stopping distance, a shorter train as well as for non-scheduled idling and a normal temperature, the resulting energy consumption is 11.5 kWh per train-km or 0.042 kWh per seat-km. At a load factor of 35 %, that is typical for this type of rail service *the resulting energy consumption in 1994 is 0.120 kWh per passenger-km.*

The typical rail traffic on this line had the following typical characteristics in the years 1994 and 2004, as shown in Table 4-2:

Table 4-2: Characteristics for older trains compared to modern trains

	1994	***2004***
Train consist	Loco + 4 cars	3 car EMU
Seating capacity	275	272
Train mass (with 35 % load factor)	261 tonnes	172 tonnes
Max speed	130 km/h	200 km/h
Number of intermediate stops	2	3
Travel time Stockholm – Västerås	78 min	53 min
Energy per seat-km (kWh)	***0.042***	***0.030***
Energy per passenger-km (kWh)	***0.120***	***0.087***

Comment: The same load factor (35 %) is assumed for the two services above. This figure is chosen because it is said to be a typical average for this type of regional services. No firm load factors are available for the services of 1994 or 2004. Because of the uncertainties in the load factors the estimations above should be seen rather as relative figures for the 1994 and 2004 services rather than exact estimates of the actual services.

4.1.3 Why are modern trains more energy efficient?

The most striking observation from the previous two sections is that *the energy consumption per seat-km or passenger-km is reduced despite the considerably higher speeds and the heavily reduced travel time. The reduction is in the range of 25 – 30 %.* How is this possible? What are the factors behind this reduction?

The general answer is that the modern train intended for higher speeds, is more developed and advanced in a number of aspects, compared to the older train. In the same time as the speed was increased and the travel time reduced a completely new type of modern trains were introduced. The main factors are explained stepwise below:

- The higher speed would have increased energy consumption by 63 %, all other factors being equal.
- The *Regina* trains have *wide bodies* (3.45 m external width) making it possible to increase the seating capacity by around 25 % compared to a carbody with normal width. The *Regina* cars are also 2.3 m longer than some of the older cars, which as an average allows an additional seating capacity per car. The resulting EMU train has 3 cars instead of the older 4-car train (plus a separate locomotive). This makes less train mass and a lower aerodynamic drag. *Due to this factor energy consumption is reduced by 26 %.*

- Modern trains, intended for higher speed, have a better *aerodynamic performance* than older trains. Modern trains are smoother along the roof and walls, and particularly underneath the main floor, where most equipment is covered. They have also longer and more streamlined noses in the front and rear ends. *This factor alone reduces the energy consumption by a further 22 %.*
- Modern electrically propelled trains have *energy recovery*. The electrical motors are used as electrical generators in the braking mode. The generated electrical energy is fed back via the pantograph to the overhead catenary, with exception of some losses. The recovered electric energy is usually utilised by other trains. If there are no trains being able to take up the regenerated energy, the voltage on the catenary will be increased to a higher level than normal; in such a case the regeneration is stopped and braking will be made by use of the ordinary mechanical brakes of the train. The measurements consider the real energy recovery, including the above mentioned limitations. *Energy recovery is 17 % of the input to the pantograph.*
- Modern trains produce *less energy loss on the overhead catenary cable and in the stationary supply stations.* This is due to the fact that modern trains have induction motor drives fed by advanced semiconductor converters. These converters allow the electrical alternating current to be fully in-phase with the line voltage. This, in turn, minimises the current taken from the overhead catenary, thus also minimising the energy losses, as the losses rises with the second power of the current.

  Also, modern feeding stations with *stationary semiconductor converters* have less energy losses, compared to the older rotary converters, as described in Section 2.2. This improvement, together with the previous one, *saves about 7 % of the energy* input to the converter station.

All these effects sum up and more than compensate the effects of the higher speeds. In the actual case, i.e. the fast regional trains Stockholm - Västerås, the energy consumption is reduced by about 27 % for a train with similar passenger capacity and the same load factor. If the load factor had increased, the energy consumption per passenger-km had been further reduced. There are indications from the operator *SJ AB* that the load factor in these regional services has increased, but we have no firm figures for the specific train services run by Regina trains.

It could be discussed whether the case should be a 3-car *Regina* train, as above, or a 2-car train. In Section 3.3 it is shown that the regional train operations (type A) is made with a mixed fleet of 2- and 3-car trains. This mixed fleet has an average energy consumption of 0.094 kWh/passenger-km, being some 8 % higher than for the 3-car train. In such a case, the improvement, compared with an old 4-car loco-hauled train, is “only” 22 %. However, if the loco-hauled train is shortened to a 3-car train, to be more comparable to a 2-car *Regina* train, the loco train would have increased its energy consumption per seat-km or passenger-km slightly more than a 2-car *Regina* train compared to a 3-car *Regina.*

4.1.4 Comments and future outlook

From the above mentioned it is clear that the modern and newly introduced trains are considerably more energy efficient than the older locomotive hauled trains. This is despite of the increased speeds that would otherwise have led to higher energy consumption. The question is whether this is a single lucky event or a more long-term trend, leading the further improvements also in the future.

The present study has not gone into a deep investigation on these matters. However, some preliminary calculations have been made in a government-supported project called

"GrönaTåget" (= Green Train), dealing with a future generation of Swedish high-speed trains. These calculations show a sustained tendency of further reducing energy consumption also in the future, despite still higher speeds, at least for long-distance trains. The preliminary calculations come up with an energy consumption in the order of 0.05 – 0.06 kWh per passenger-km for Swedish main-line operations at speeds up to 250 km/h. This is for a future six-car wide-body EMU train with a seating capacity of approx 450 seats (of which 30 % are in 1st class) and a load factor of 55 %, i.e. the same as the current *X 2000.* This is a further 20 – 30 % reduction compared to the previously investigated and reported *X2000* operations, which - in turn - were almost 30 % better than the previous loco-hauled trains. Although these calculations have to be finally confirmed the possibilities and the tendencies seem to be clear.

Other potential means of energy savings could be implemented on modern trains. New systems for optimized train control and communication, train positioning and time-tabling could be developed and introduced.

4.2 Some comparisons with other modes of transport

Electric trains are said to be "environmentally sound" as compared to most other modes of transport, in particular with regard to energy consumption and the related emissions of greenhouse gases and other air pollution.

In this study no attempt has been made to determine energy consumption and air pollution for other modes than trains. However, in order to relate the fairly abstract average figures of energy consumption and the related air pollutions for trains, some comparative figures have been extracted from NTM (Nätverket för Transporter och Miljön; *Eng:* Network for Transport and Environment) [7], a Swedish non-profit organisation aiming at establishing a common base of values on how to calculate the environmental performance for various modes of transport. These figures are being considered as typical average for modern passenger transport, all being made with modern vehicles introduced during the period 1995 – 2004.

The comparisons are made for two types of service, one long-distance and one regional journey:

(1) Stockholm-Göteborg (455 km railway distance) made by an *X 2000* train; see Table 4-3.

(2) Stockholm – Västerås (107 km railway distance) made by a *Regina* train; see Table 4-4.

Table 4-3: Energy consumption and emissions of air pollutions for train and other comparable transport modes - case Stockholm – Göteborg (455 km)

	Energy	*Average emissions per pass-km*		*Marginal/Green emissions per pass-km*	
	(kWh, fuel litres)	*CO_2 (g)*	*NO_x (mg)*	*CO_2 (g)*	*NO_x (mg)*
Train					
- X 2000, 6 cars	13.6 kWh el/km				
(176 pass / 320 seats)	0.077 kWh/p-km	7	16	0 / 0.006	0 / 0.021
Airplane					
– Boeing 737-800	5.9 lit kerosene/km				
(116 pass / 179 seats)	0.51 kWh/p-km	130	600	130	600
Bus					
- Euro 3 emissions	0.40 lit diesel/km				
(20 pass / 59 seats)	0.20 kWh/p-km	53	360	53	360
Private car					
– Medium size	0.070 lit petrol/km				
Mk 2000	0.35 kWh/p-km	87	40	87	40
(1.8 persons / 5 seats)					

Table 4-4: Energy consumption and emissions of air pollutions for train and other comparable transport modes - case Stockholm – Västerås (107 km)

	Energy	*Average emissions per pass-km*		*Marginal/Green emissions per pass-km*	
	(kWh, fuel litres)	*CO_2 (g)*	*NO_x (mg)*	*CO_2 (g)*	*NO_x (mg)*
Train					
- Regina, 3 cars	8.3 kWh el/km				
(95 pass / 272 seats)	0.087 kWh/p-km	8	18	0 / 0.006	0 / 0.023
Bus					
- Euro 3 emissions	0.45 lit diesel/km				
(20 pass / 59 seats)	0.22 kWh/p-km	59	405	59	405
Private car					
– Medium size	0.075 lit petrol/km				
Mk 2000	0.37 kWh/p-km	93	43	93	43
(1.8 persons / 5 seats)					

Conclusions and comments to Tables 4-3 and 4-4:

- Electric trains still have an outstanding low energy consumption and air pollution compared with other common transport modes. This is in spite of the higher average air pollution from the Nordic electric power market compared with the average Swedish electric power production. It is also in spite of improvements in air pollution control that have taken place for many types of buses, cars and airplanes over the last 25 years.
- In the above estimations electricity as taken from the public grid is considered. The energy content in the fuel as delivered to the fuel tank is assumed.
- The "average" case is related to the average electric energy from the Nordic market for electric power exchange, as defined in Section 2.4.1.
- The "marginal" case is the short, intermediate or long-term marginal effects of increased transportation as defined in Section 2.4.2, A constant typical load factor of today is assumed for all means of transport. Vehicle technology is assumed to be as of today in all the mentioned vehicles. In reality technology is expected to be improved for all means of transport, however, these issues are not covered in this study.
- The "green" case relates to the use of "green" electric energy defined in Section 2.4.3.
- The energy consumption figures for different means of transport are not fully comparable straight off. For electric trains these figures relate to the electric energy taken from the public electric grid. Figures for the other transport means (aircrafts, buses and cars) relate to the energy content in the liquid fuels filled into the fuel tank. A certain amount of electric energy on the Nordic market is produced with energy losses (i.e. with an energy efficiency considerably less than 100 %) not being considered in above comparison. On the other hand, the resulting air pollution takes these losses into consideration. Further, energy losses and emissions in fuel production and transport are not considered for aircrafts, buses and cars.
- If marginal contributions of air pollutions are considered, the production of the additional electric energy needed for rail transport will be made in a way that will not generate any – or very low - additional emissions of carbon dioxides (CO_2). This is due to the newly introduced EU emission trading scheme.

5 Summary and conclusions

Determination of energy consumption - methodology

In the present study the energy consumption of a number of modern Scandinavian electric passenger train operations is determined: *X 2000, Regina, OTU, Type 71* “Flytoget” and *Type 73* “Signatur”. The investigated trains are all designed and manufactured by Bombardier Transportation (Sweden). Energy measurements are made in regular train operations for all the investigated trains. Measurements on new trains (introduced since 1999) are made in the years 2002-2005. For *Regina* and *Flytoget* long time series are available, while shorter time series have been used for the other trains.

Energy consumption data from 1994 have been used in two cases: for the actual operations of *X 2000* and for comparisons with older loco-hauled trains. Data from these two trains have been adjusted for the actual operational conditions by calculation.

Air pollutions

Also, the resulting air pollution from the production of the used electric energy is being determined. As a first alternative in this study, the *average* air pollutions on the common Nordic market for electrical power are being determined for the years 2000-2004. In this respect it is important to know by what means the electric power is produced. On the common Nordic market for electric power (Denmark. Finland, Norway and Sweden) a number of different means are used.

However, there might sometimes be good reasons to consider not the average but rather the *marginal effects*, i.e. the additional contributions for an additional rail passenger or an increased rail passenger transport in general. In the short term an additional passenger in a scheduled train generates an almost negligible marginal effect. In an intermediate or long-term perspective – where an increased amount of trains, or longer trains, are needed – more energy will be consumed for train operations. This would be the case if future possible improvements in energy performance are neglected.

Since 2005 a new regulatory framework – the EU emissions trading scheme (ETS) - is applicable to electric power production within Europe. It is aimed at reducing greenhouse gas emissions according to the Kyoto obligations, by allocating gradually reduced emission allowances to different sectors and entities. If one entity is not able to reduce its emissions, or wants to even increase them, that entity must buy allowances from another entity being able to reduce emissions at a cost less than the price of the transferred allowances. At the current stage (2005-2007) only emissions of carbon dioxide (CO_2) is regulated. As a result of this *the marginal contribution of CO_2 resulting from an additional need for electric energy will be zero,* provided that the allowances in a long-term perspective are utilised close to the limit.

The authors to this report find it most likely that also other emissions will be reduced considerably, due to the transition from burning fossil fuels to other technologies and also a general modernisation of electric energy production. An increased need for electric energy will likely speed up this process. In particular this will be the case if also other greenhouse gases will be regulated in later stages. *The authors of this report propose the hypothesis that the future marginal contribution of NOx, HC and CO will be close to zero.*

Main results

As a result of this study typical energy consumption figures – and resulting air pollution - is determined for the different long-distance and regional train operations with different load factors. An extract of the results are presented in the table below. Energy is determined as taken from the public electrical grid, used for propulsion, onboard comfort as well as for idling outside scheduled operations. Thus the presented figures include energy losses in the power supply system.

Train *LF = Load Factor*	***Electric energy per pass-km***	***Average Nordic emissions per pass-km***		***Marginal / Green emissions per pass-km***	
	(kWh)	*CO_2 (g)*	*NO_x (mg)*	*CO_2 (g)*	*NO_x (mg)*
X 2000 (long-distance) LF = 55 %	0.077	7	16	0	≈ 0
Regina 3-car train (fast regional, type A) LF = 35 %	0.087	8	18	0	≈ 0
Regina 2-car train (fast regional, type B) LF = 20 %	0.168	16	35	0	≈ 0
Øresundstoget (OTU) (fast regional) LF = 41 %	0.069	7	14	0	≈ 0
Type 71 - Flytoget (fast airport train) LF = 27 %	0.182	18	38	0	≈ 0
Type 73 – " Signatur" (long-distance) LF = 60 %	0.079	8	16	0	≈ 0
Comparison with typical operations of year 1994:					
X 2000 (long-distance) LF = 44 % (assumed)	0.103	10*	21*	Not investigated	
Loco-hauled 8-car train (InterCity) LF = 44 %	0.108	10*	22*	Not investigated	
Loco-hauled 4-car train (regional) LF = 35 %	0.120	12*	25*	Not investigated	

*) Corrected for the Nordic common market for electric power

If energy was measured at the train's current collector (pantograph), i.e. if losses in the railway power supply system were excluded, the energy consumption would be 9 – 14 % less.

From the data shown above it is clear that energy consumption as measured per passenger-km is very dependent on the actual load factor. Modern long distance trains have generally a quite high load factor, while regional trains in more sparsely populated areas sometimes have a considerably lower load factor. Fast regional trains in more densely populated areas are usually in between these extremes.

However, also in the cases with a low load factor the trains are very competitive to other modes of transport with regard to energy consumption and emissions.

Modern electric passenger trains have improved energy efficiency

It is evident that the trains successively introduced in the last 10 years (1994 – 2004) are typically 25-30 % more energy efficient than the older traditional loco-hauled trains, in spite of the considerably higher speeds and the reduced travel time. Generally speaking, the new trains intended for modern operations at higher speeds are improved in a number of aspects compared to the older trains, i.e. they are well adapted to the higher speeds.

Firstly, modern trains have a better aerodynamic performance which reduces the air drag and thus the energy consumption at higher speeds. Secondly, modern trains are equipped with regenerative braking facilities, allowing energy recovery when braking or running downhill. The recovered electric energy is mainly being fed back to other trains. Thirdly, the energy efficiency of the railway's electric power supply system has been improved, partly due to more advanced technologies of the trains.

Also, the older loco-hauled trains are substituted by multiple-unit trains, having propulsion equipment built into the same car as the passenger compartment, which has reduced the train mass per seat. In one case – the *Regina* train – this tendency is further enhanced by the wide carbody allowing some 25 % more seats per meter of train.

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Appendix

Average electric power production from various sources on the Nordic common market

Year 2000 - 2004

Source	Denmark [TWh]	Country [%]	Nordic [%]	Finland [TWh]	Country [%]	Nordic [%]	Norway [TWh]	Country [%]	Nordic [%]	Sweden [TWh]	Country [%]	Nordic [%]
Wind power	**5,1**	13,6	1,3	**0,1**	0,1	0,0	**0,1**	0,1	0,0	**0,6**	0,4	0,2
Other	**2,0**	5,3	0,5	**0,5**	0,7	0,1	**0,5**	0,4	0,1	**0,3**	0,2	0,1
Bio fuel	**1,9**	4,9	0,5	**10,4**	13,5	2,7	**0,1**	0,0	0,0	**4,6**	3,2	1,2
Peat	**0,0**	0,0	0,0	**6,3**	8,2	1,7	**0,0**	0,0	0,0	**0,0**	0,0	0,0
Natural gas	**9,3**	24,7	2,4	**9,5**	12,4	2,5	**0,3**	0,2	0,1	**1,1**	0,7	0,3
Oil	**0,8**	2,2	0,2	**1,7**	2,2	0,4	**0,0**	0,0	0,0	**3,0**	2,1	0,8
Coal	**18,5**	49,2	4,8	**14,2**	18,5	3,7	**0,0**	0,0	0,0	**2,1**	1,4	0,5
Nuclear power	**0,0**	0,0	0,0	**21,7**	28,3	5,7	**0,0**	0,0	0,0	**66,0**	45,6	17,3
Hydro power	**0,0**	0,1	0,0	**12,5**	16,2	3,3	**121,6**	99,2	31,9	**67,0**	46,3	17,5
Total country	**37,6**			**76,8**			**122,6**			**144,6**		
Total nordic	**381,6**											