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Estonian electricity supply scenarios for 2020 and their environmental performance

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Abstract

Estonia is the only country in Europe with significant environmentally intensive oil shale-based energy production. However, the legal obligations of the EU will make substantial changes over the coming years to current electricity production technology. Increasing the use of alternative energy carriers for responding to future requirements has also been in focus. In this study, three different future electricity supply scenarios for Estonia in 2020 are considered and compared to the situation in 2002. They are based on domestic oil shale, imported natural gas, and imported nuclear power. According to the aims of the national energy policy, renewable energy sources were raised to 10% in all scenarios. Using the LCA methodology, the least damaging impact on the environment occurs in the 'nuclear scenario', with nuclear energy as the main energy source. The best scenario, however, depends on the weight or acceptance of accidental releases or other impacts not defined in this context. The 'Oil shale scenario' would be a slightly more damaging alternative than the 'Natural gas scenario' even if new technical solutions will remarkably improve the environmental performance of oil shale electricity production. Land use and waste disposal are crucial issues, particularly for oil shale and nuclear electricity production. However, the depletion of oil shale is not as critical an issue as the depletion of natural gas and uranium. According to the significance analysis of impact categories, climate change is the most significant impact on the environment in the scenarios. Future decisions on the development of the Estonian energy sector are most likely to be based on technological, economical and political aspects. Political aspects are likely to be the most significant. However, this type of study can give additional value to the discussion due to the increasing role of sustainability in energy issues.

Keywords: Electricity; Life cycle assessment; Scenario

1. Introduction

Estonia is the only country in Europe which has a significant oil shale mining industry. The oil shale power plants produce approximately 92% of Estonian electricity, making oil shale energy production a strategic industry in Estonia. The production of oil shale electricity utilises extensive amounts of natural and human resources. It was during the 1940s when the decision was made to use Estonian fossil fuel widely in the chemical industry and in energy production for Estonia and the north-western part of the Soviet Union (Russian St. Petersburg Region). Nowadays the annual amounts of mined oil shale and generated electricity have substantially decreased, but the characteristics of emissions have not changed substantially, and the environment in the north-eastern part of Estonia is still largely affected by the oil shale industry (Gavrilova et al., 2005).

In 2004, Estonia became a member of the European Union (EU). After a transition period, legal obligations will make unavoidable changes over the coming years to the technology of oil shale-based electricity production. The focus is on the fulfilment of directives regulating environmental protection, pollution, waste, greenhouse gas (GHG) emissions and more. In order to assess the

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alternatives for electricity supply in the future, the environmental impacts must be taken into account together with economic and technical aspects.

This paper presents the results of Task 4 of the EU Life Environment project, OSELCA,[1] in which future electricity supply options for Estonia and their environmental performance were considered. The two main objectives of this subproject were:

- to design future electricity supply scenarios for Estonia based on technological developments, political decisions and legislative commitments, and
- to give an overview of the environmental performance of the scenarios using the life cycle assessment (LCA) methodology.

Starting points for the calculations were the current electricity consumption, the estimated electricity consumption in 2020, and different future energy supply profiles. In addition, the development possibilities in power plant technology have been taken into account.

2. Construction of Estonian electricity supply scenarios

2.1. Methodological basis

2.1.1. Background materials on Estonian energy policy

A recent policy document regarding the development of Estonia's energy and electricity generation until the year 2015 (Ansip, 2004) introduced strategic guidelines and the main goals of the Government of Estonia in the field of energy. According to the guidelines domestic consumption needs shall be covered by domestic electricity production capacity. The aim is that the share of renewable energy resources will reach 5.1% of the electricity gross consumption in 2010, decreasing the share of oil shale as the main local fuel from a long-term perspective. In order to increase the efficiency of the power plants and fulfil the environmental requirements, the production of oil shale energy/electricity will be transferred to fluidised bed technology. Current electricity and heat co-generation capacities will be preserved and the establishment of new CHP (combined heat and power) plants in regions with adequate heating needs are favoured. The proportion of co-generated electricity must increase from 13% to 20% of the electricity gross consumption by the year 2020.

By the request of a state owned energy company Eesti Energia, Tallinn Technical University has prepared a strategic energy plan until the year 2030 (Eesti Energia, 2004). It is in line with the previous plan emphasising the importance of renewable energy recourses (which must reach 10% of the electricity gross consumption by the year 2020) and the development of co-generation electricity.

2.1.2. Trends for energy supply scenarios

In the main strategy policy documents, it is clearly stated that Estonia has to maintain its ability to cover electricity consumption by domestic electricity production capacities whilst adding the use of renewable energy resources. According to these principles, '*oil shale scenario 2020*' and '*natural gas scenario 2020*' were designed. Additionally, '*nuclear scenario 2020*' for Estonia was designed considering the possibility of increasing the use of nuclear power. The basic situation to which the future scenarios are compared is the energy supply profile in Estonia in 2002, and is called '*Current 2002*'.

The 'oil shale scenario' most resembles the current situation. However, all operational oil shale boilers are considered to be renovated by the year 2020. The extent of necessary renovations is currently under investigation and the decision concerning the total number of removable blocks depends on the outcome of the first renovated blocks (i.e. decrease of emissions, economic cost-benefit). The renovation involves the transferring of the blocks to fluidised bed technology. In addition, the ash removal systems need modifying to the new "*dry*" or "*semi-dry*" technology. This modification means that large amounts of water are saved in the oil shale ash removing stage. Current "*wet*" ash removal system generates enormous amounts of liquid waste, which is classified as hazardous because of its high alkalinity.

For the 'natural gas scenario', an assumption of the continuing Russian competitive natural gas price was made. The gas price situation could—and probably will—drastically change because the current price for Russian import gas is the cheapest in Europe. If the natural gas price starts to rise, the competitiveness of natural gas shall decline accordingly.

The key factor for the 'nuclear scenario' is the up and coming trade of GHG emissions—their prices and quantities in addition to other Kyoto protocol implementing mechanisms. This could work through channelling investments into nuclear electricity generation plants abroad (due to technical and economical reasons it would not be practical in Estonia). Income from the GHG trade could serve as a source for this kind of investment. It would be reasonable to invest somewhere, where the necessary competency, infrastructure and geological conditions already exist.

2.1.3. Electricity consumption

Electricity consumption in the current situation 2002 was calculated by the following formula:

$$\begin{aligned} Consumption &= Gross\ production - power\ plants\ self\ use \\ &- losses - export + import. \end{aligned}$$

Estonia's electricity gross production in 2002 was 8527 GW h (Statistical Office of Estonia, 2004), from

[1]OSELCA, introduction and implementation of life cycle assessment methodology in Estonia: effects of oil shale electricity on the environmental performance of products, 2003–2005. Eesti Energi Ltd, Cycleplan Ltd, Finnish Environment Institute (www.energia.ee/OSELCA).

which the power plants self-use 893 GW h reported by Eesti Energia, leaving for the net production 7634 GW h. According to this formula, in which the whole national energy balance including exports and imports was taken into account, the current (2002) electricity consumption in Estonia was 5686 GW h (Table 1).

The value of electricity demand forecast for the year 2020 was predicted based on Eesti Energia (2004), where a moderate annual increase of 2.00–3.75% was considered. The final electricity consumption figure (8350 GW h) constitutes a total growth of 46.9% over 18 years compared with the same figure in 2002.

2.1.4. Current electricity supply situation

The importance of the oil shale industry to current Estonian electricity production is well identified. In the basic scenario, which also includes importation, a large proportion (87.6%) of used electricity was produced using solely oil shale (Statistical Office of Estonia, 2004)—including oil shale condensation (cond.), oil shale co-generation (CHP, combined heat and power), oil shale (carbonisation) gas and shale oil (Table 2, Fig. 1).

Estonia itself does not have nuclear-based electricity production. However, the current electricity supply scenario has a minor share of imported nuclear energy from Russia and Lithuania. Imported electricity from Russia was assumed to include 50% nuclear, 30% natural gas (condensation) and 20% hydro energy. In the case of Lithuanian electricity imports, the shares were 77.3% for nuclear, 15.1% for natural gas (co-generation), 5.3% for hydro and 2.3% for heavy fuel oil.

In the 'Current 2002' scenario, the share of hydro-based electricity reaches 4%, while Estonia itself generated only about 0.1% of this in 2002 (Statistical Office of Estonia, 2004). The imported electricity from Latvia was considered to be hydro energy as a whole. Russia and Lithuania have their own hydro energy shares as well.

Table 1
Total electricity consumption in Estonia in 2002

Year 2002	Electricity (GW h)						
	Gross production	Self use	Losses[a]	Export		Import	
	8527	893	1258	To Russia	396	From Russia	76
				To Latvia	706	From Latvia	200
				To Lithuania	0	From Lithuania	136
Total	8527	893	1258		1102		412
					Total consumption 5686 GW h		

[a]Losses caused by distributing networks and company's equipment.

Table 2
Electricity consumption divided by energy sources in the current situation (2002) and in different scenarios for 2020

Energy source	Electricity consumption (GW h)			
	Current 2002	Oil shale scenario 2020	Natural gas scenario 2020	Nuclear scenario 2020
Fossil fuels				
Oil shale	4979.2	7804.4	3123.0	3123.0
Oil shale condensation	4587.3	7597.4	2916.0	2916.0
Oil shale co-generation	281.6	180.0	180.0	180.0
Oil shale gas	94.5			
Shale oil	15.8	27.0	27.0	27.0
Natural gas	333.2	1966.9	6648.3	1966.9
Natural gas co-generation	310.4	1696.9	3498.3	1696.9
Natural gas condensation	22.8		2250.0	
Natural gas turbine		270.0	900.0	270.0
Heavy fuel oil	3.7	4.5	4.5	4.5
Peat		27.0	27.0	27.0
Nuclear (import)	143.1			4681.8
Renewable resources	226.8	1089.0	1089.0	1089.0
Wind energy	0.6	711.0	711.0	711.0
Bio-mass co-generation (wood)[a]		288.0	288.0	288.0
Hydro energy	226.2	76.5	76.5	76.5
Bio-gas co-generation		13.5	13.5	13.5
Total	5686	10 892	10 892	10 892

[a]Bio-mass (wood) is assumed to include wood chips, -pellets and other wood-based fuels.

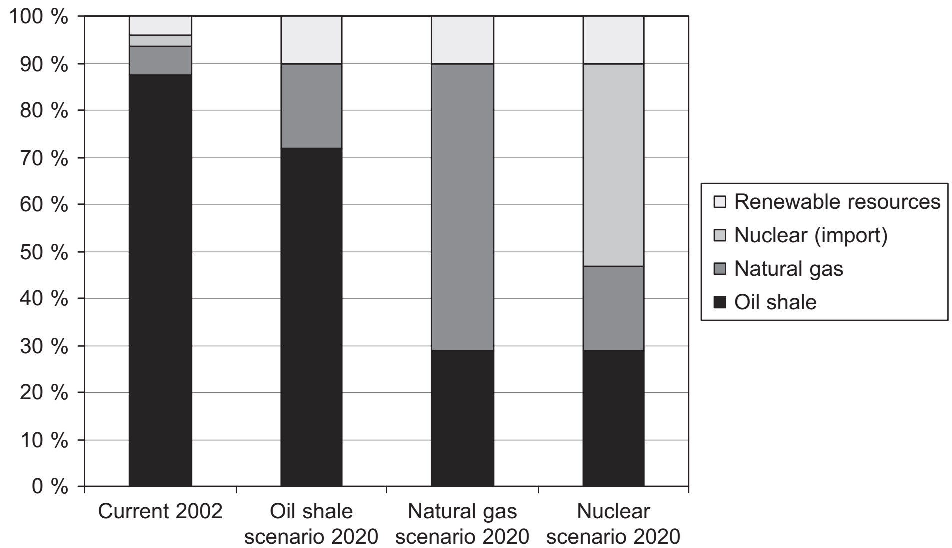

Fig. 1. Energy sources in the current and future electricity supply scenarios for Estonia.

2.2. *Electricity supply scenarios in 2020*

2.2.1. *Oil shale scenario*

Oil shale serves as the main source of electricity in the 'oil shale scenario' (Table 2, Fig. 1). However, compared to the 'Current 2002' scenario, the share of oil shale electricity has decreased—from 85% to 70%. The share of renewable energy is reaching the target level (10th of gross production) by the year 2020. There is a remarkable increase in wind energy which acquires a 6.5% share. This is quite significant when compared to 2002, where there was not enough wind-based electricity, not even reaching a 0.1% share of the scenario. In addition the proportion of co-generated electricity will increase, up to 20% of the electricity gross consumption. The main reason is natural gas, which increases by almost 10% compared to the situation in 2002.

2.2.2. *Natural gas scenario*

For the 'natural gas scenario', imported natural gas from Russia is considered as the main substitute for the oil shale electricity production capacity (Table 2, Fig. 1). In this scenario, the main source of electricity generation is natural gas with a total share of 61.1% (including condensation, co-generation and turbine). The next largest source would be oil shale (28.5%) and the majority of the rest consists of renewable resources—with the same proportion as in the oil shale scenario (10%). The oil shale share includes only renovated blocks and boilers, thus reflecting the maximum investment into oil shale-based electricity production capacities.

2.2.3. *Nuclear scenario*

In the 'nuclear scenario', electricity is imported to cover domestic short falls, avoiding the investments in domestic (additional) production capacities (Table 2, Fig. 1). Nuclear electricity replaces natural gas produced electricity, and dominates with a share of 43%. The other resources remain unaffected compared to previous scenarios.

3. Environmental performance of electricity supply scenarios

3.1. *Assessment of environmental interventions*

The aim of the study was to find out how environmental performance differed between the electricity supply scenarios, and not to perform detailed LCAs on different production forms. Therefore the basic life cycle inventory (LCI) data (except oil shale data, Talve et al., 2005) was gathered from the generic Ecoinvent database (Ecoinvent, 2005). Data include environmental interventions such as emissions, resource extraction and land use. The inventory data of the product systems were collected and documented applying the ISO 14041 standard (ISO, 1998; Koskela et al., 2005).

In order to make comparisons, 1 MW h *of grid electricity* was used as a functional unit in each scenario inventory, i.e. all inputs and outputs of the production system were calculated per 1 MW h electricity consumed in Estonia. In Table 2, the scenarios are presented with all the production forms. However, in the LCI calculations the minor share of electricity generation forms (heavy fuel oil and biogas) were omitted or added to other electricity forms. The share of oil factory products (shale oil and semicoke gas) was added to the oil shale (condensation) electricity, and peat and biomass to the wood electricity, respectively. In addition, radioactive emissions and transmission losses were not included in the calculations.

As the focus of the scenarios was the future, it was important to take the technological development of power plants and resultant improvements in environmental performance into account. This was achieved by modifying current or database data in order to correspond

Table 3
Corrections to efficiency/emission factors reflecting future power plant technology

Efficiency/emission	Current/basic	Corrections for future scenarios
Oil shale power plants		
Efficiency	Data from Talve et al. (2005)	Improved 20%[a]
CO_2	Data from Talve et al. (2005)	Decreased 20%[a]
SO_2	Data from Talve et al. (2005)	Decreased 99.7%[a]
NO_x	Data from Talve et al. (2005)	Decreased 40%[a]
Particles	Data from Talve et al. (2005)	Decreased appr. 70%[a]
PM_{10}	71% from total particles[b]	85% from total particles[b]
$PM_{2.5}$	30% from total particles[b]	41% from total particles[b]
Wood combustion plant		
$PM_{2.5}$	Data from ecoinvent database	Decreased 91%[c]
Natural gas power plants		
Efficiency	Data from ecoinvent database	41% in condensation, 38% in turbine, 40% in CHP plants[d]
NO_x	Data from ecoinvent database	CHP: modified to fulfill EU legislation[e]

[a]Foster Wheeler (2005).
[b]Expert judgment based on Aunela-Tapola et al. (1998) and Karvosenoja and Johansson (2003a, b).
[c]Karvosenoja and Johansson (2003a, b).
[d]Finnish Environment Institute (2001).
[e]Large Combustion Plants Directive (2001/80/EC).

with the technical performance of modern power plants (Table 3).

3.2. Impact assessment method

In this study, the LCI data of the production systems were interpreted using the life cycle impact assessment (LCIA) method presented by Seppälä et al. (2006a). The method corresponds to the recommendations of the International Organisation for Standardisation (ISO 14042, 2000). In the LCIA method, the values of environmental interventions are multiplied by the corresponding characterisation factors. Due to multiplication the values of interventions are converted into the same unit expressing the effects of a chosen indicator. Thus, the impact category indicator results can be summarised within each impact category. In the LCIA method, the following impact categories with characterisation methods (in brackets) for calculating category indicator results were used:

- climate change (IPPC, 1996);
- acidification (Seppälä et al., 2006b);
- tropospheric[2] ozone formation (Hauschild et al., 2005);
- aquatic eutrophication (Seppälä et al., 2004);
- terrestrial eutrophication (Seppälä et al., 2006b);
- ecotoxicity (Hauschild and Potting, 2005);
- particulate matter ($PM_{2.5}$);[3]
- depletion of fuels (Guinée and Heijungs, 1995); and
- other impacts (no characterisation).

[2]The troposphere is the lowest layer of the atmosphere. It extends from the Earth's surface up to about 16 km.
[3]Particulate matter less than 2.5 μm in diameter.

The 'other impacts' category includes impact categories that have no scientific characterisation factors or data on their environmental interventions are difficult to assess. These impact categories are for example toxicity to humans, the amounts of recycled and deposited wastes, and depletion of biodiversity due to land use. In addition, radioactive releases are included in this group. In the study, the impact assessment of these impact categories between the scenarios was conducted according to a qualitative approach instead of using characterisation.

The normalisation phase of LCIA was conducted in order to help interpret the significance of the impact categories compared with each other. The impact category indicator results of the production systems were divided by the available corresponding European reference values in 2002 presented by Seppälä et al. (2006a).

3.3. Results and discussion

3.3.1. Characterisation results and their significance

In this study, the emissions gathered in the inventories of different scenarios were interpreted from the viewpoint of environmental effects. The results of the characterisation phase (aggregation of emissions according to different impact categories) are illustrated in Figs. 2–6. The figures show the relative contribution of the different scenarios to each impact category. In addition, amounts of $PM_{2.5}$ emissions are given in Fig. 7. Finally, the results concerning the significance of category indicator results were discussed with normalisation results.

3.3.1.1. Climate change. The term 'climate change' describes a range of impacts caused by the contribution of so called 'GHG' to global warming.

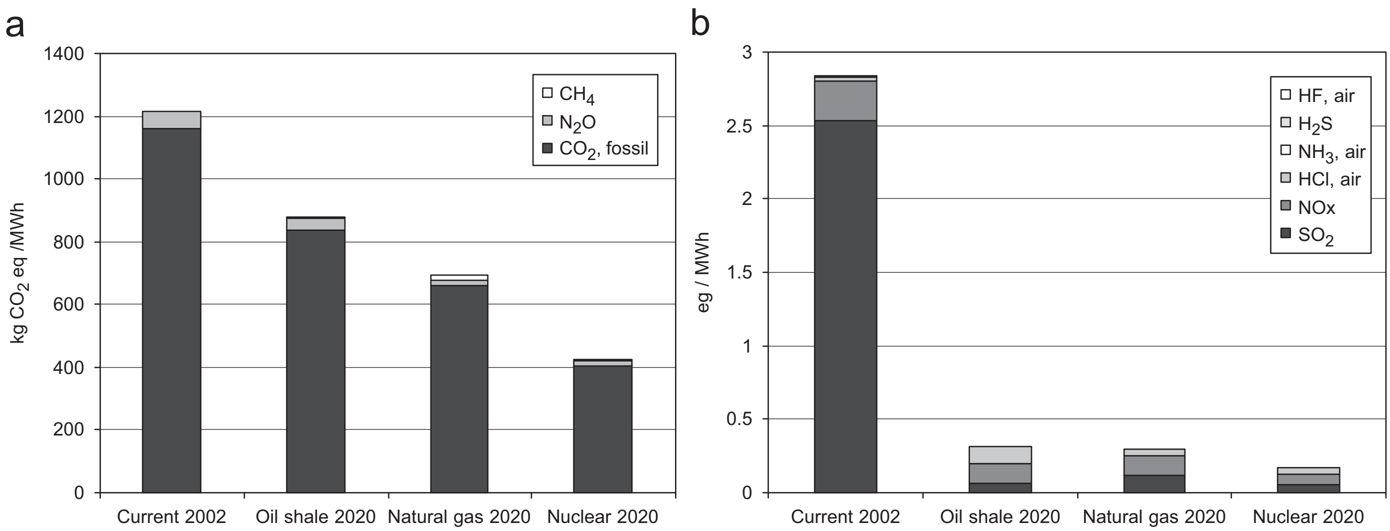

Fig. 2. The contribution of different scenarios to climate change [kg CO_2 eq/MW h] and to acidification [eq/MW h].

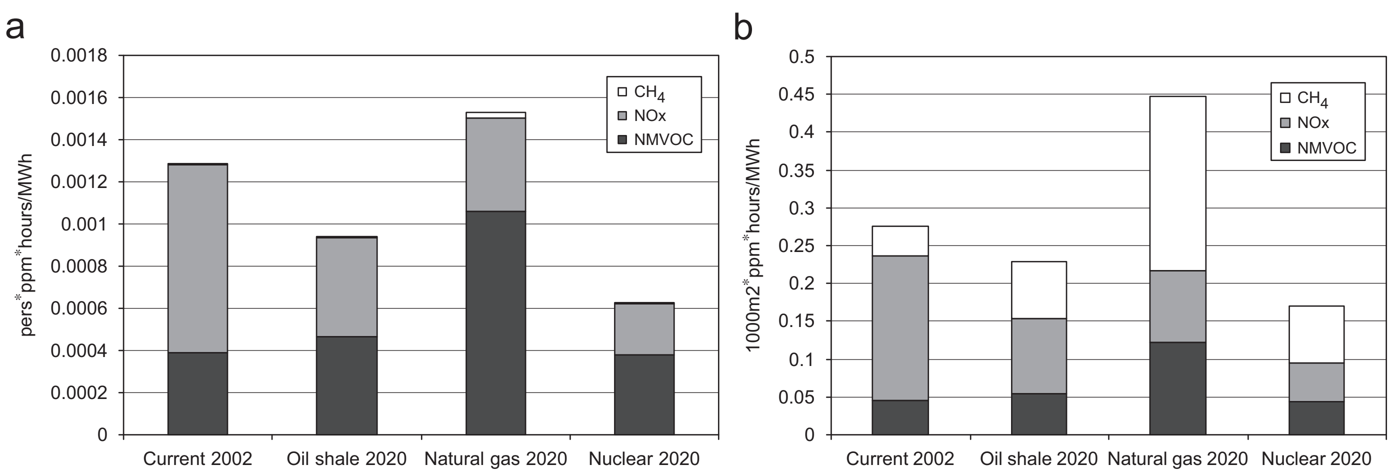

Fig. 3. The contribution of different scenarios to tropospheric ozone formation, human health effects [pers ppm h/MW h] and effects on vegetation [1000 m^2 ppm h/MW h].

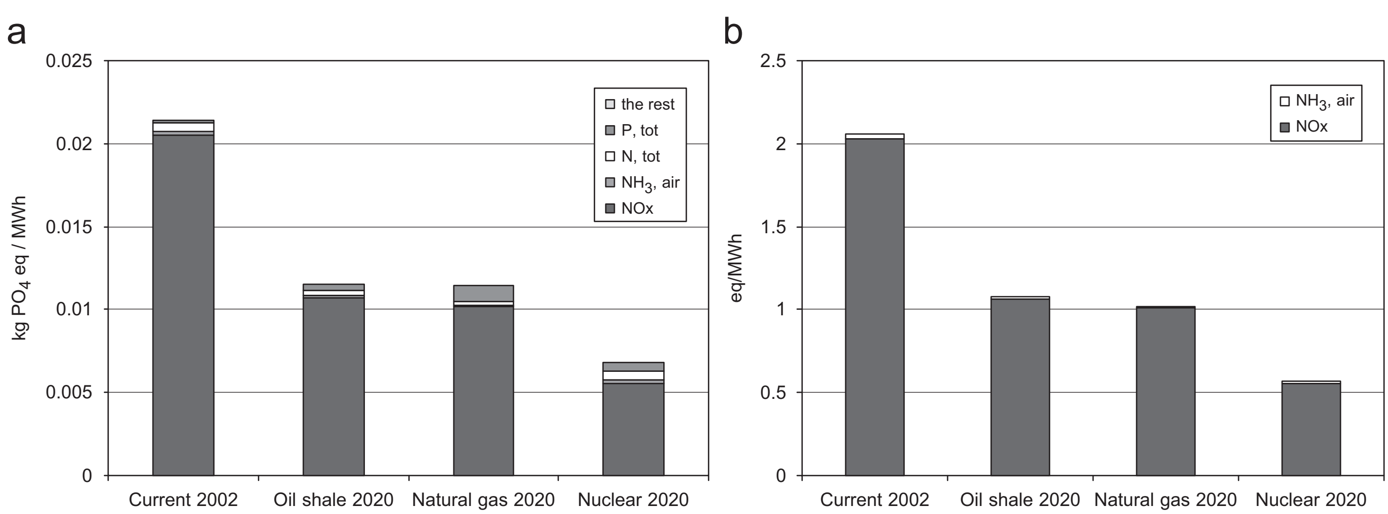

Fig. 4. The contribution of different scenarios to aquatic eutrophication [kg PO_4 eq/MW h] and to terrestrial eutrophication [eq/MW h].

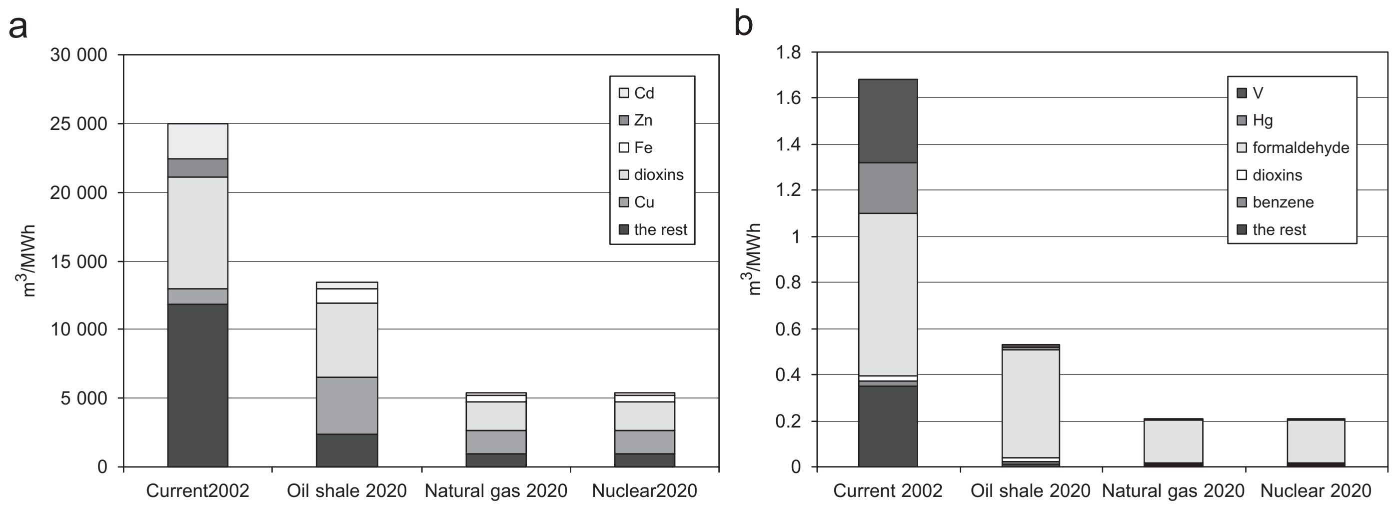

Fig. 5. The contribution of different scenarios to: (a) chronic aquatic ecotoxicity and (b) chronic terrestrial ecotoxicity.

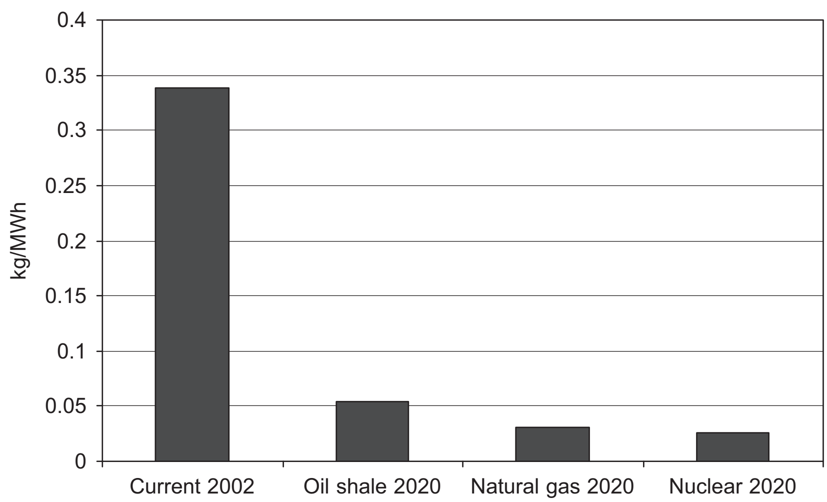

Fig. 6. The amount of $PM_{2.5}$ particulates for each scenario [kg/MW h].

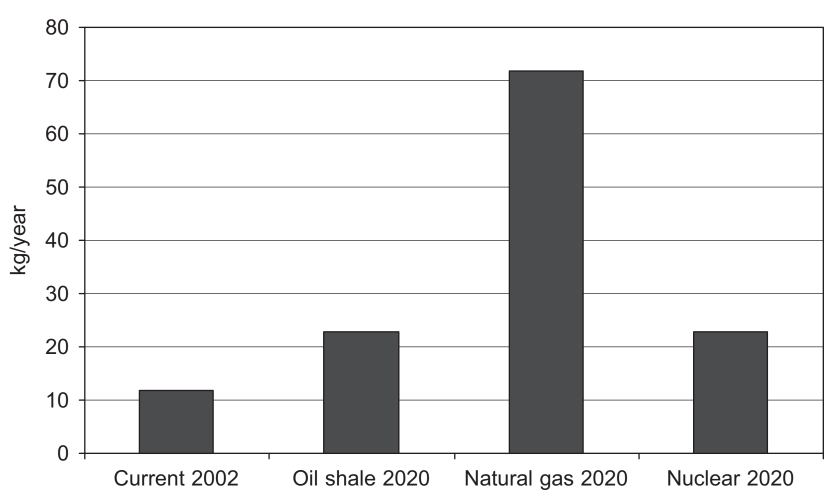

Fig. 7. Depletion of oil shale, natural gas and uranium in the current situation and future scenarios.

Electricity production in power plants causes the majority of GHG emissions. The 'Nuclear scenario' has the most favourable impact on climate change (Fig. 2a). The worst situation occurs in the current electricity supply profile. The future oil shale scenario cannot match the other scenarios, even though the new power plant technology of oil shale electricity production is assumed to reduce the CO_2 emissions by 20% (Foster Wheeler, 2005). The reductions between the 'Current 2002' scenario and the 'oil shale scenario' can be explained partly by improved efficiency of oil shale electricity production and partly by the difference in the shares of oil shale electricity in the scenarios. This also affects the results of all other impact categories.

3.3.1.2. Acidification. Acidification refers to the wet or dry deposition of acidic substance from anthropogenic origin on the earth's surface and most commonly occurs through acid rain. Acidification can change the pH of an environment and can indirectly cause toxic effects on plants and aquatic organisms. Acid rain also dissolves cement and minerals of buildings in urban environments.

The greatest change between the current situation and the 'oil shale scenario' takes place in the impact category 'acidification' which reduces by approximately 90% (Fig. 2b). It is assumed that by applying new combustion technologies and efficient emission reduction techniques, SO_2 emissions, being the main source of acidification, would fall significantly (see Table 3). The acidifying emissions from natural gas combustion and nuclear power are minimal compared to the burning of oil shale. On average the SO_2 emissions from nuclear power are approximately half of those from the combustion of natural gas (Dones et al., 2005).

3.3.1.3. Tropospheric ozone formation. Tropospheric ozone formation means the formation of ozone by the action of sunlight on certain primary pollutants (nitrogen oxides (NO_x), volatile organic compounds (VOC)). Ozone that is formed in the troposphere contributes to smog causing respiratory problems in humans and damage to vegetation.

This impact category is divided into two subcategories considering separately the effect on human health and the effects on vegetation (Fig. 3a and b). In the 'Natural gas scenario', the production of natural gas causes most of the VOC and methane emissions, which are the main contributing emissions in tropospheric ozone formation. Most of the non-methane volatile organic compounds (NMVOC) emissions are released in the production stage, whereas methane is released most of all during long-distance transport (Dones et al., 2005). The emissions of nitrogen oxides (NO_x) mostly caused by oil shale electricity production also form ozone in Northern Europe. For this reason, the influence of oil shale electricity on the results of different scenarios is also significant.

3.3.1.4. Aquatic and terrestrial eutrophication. Aquatic eutrophication can be defined as the state of a water body in which the production and accumulation of algae and higher aquatic plants have increased excessively due to the increased input of nutrients. Eutrophication can result in undesirable changes in water quality and on the biological populations of the water body. Terrestrial eutrophication refers to a state of increased nutrient availability in soil increasing the growth of vegetation.

The ranking of the scenarios in the impact categories of aquatic and terrestrial eutrophication is the same as the ranking for climate change and acidification categories (Fig. 4a and b). The contribution of NO_x emissions to eutrophication dominates. Depending on the technology, NO_x emissions are approximately ten times greater in the natural gas combustion than in the production of nuclear power (Dones et al., 2005). In the future oil shale technology, the decrease of NO_x emissions is not as remarkable as in the case of SO_2 (see Table 3).

3.3.1.5. Ecotoxicity. Ecotoxicity includes various chronic and acute effects on natural organisms. In this work, the impact category is divided into two subcategories; chronic aquatic and terrestrial ecotoxicity.

In the ecotoxicity categories 'natural gas and nuclear scenarios' cause a similar impact. Due to the metal emissions from oil shale electricity generation the 'oil shale scenario' causes a more harmful impact than the other two, although the improvements in the efficiency and the emission reduction techniques have been taken account. The natural gas combustion causes mercury emissions but no other metal emissions.

3.3.1.6. Particulate matter. Ambient concentrations of particulate matter in air cause chronic and severe respiratory and cardiovascular symptoms as well as increased mortality in humans. Primary particulate matter consists of primary and secondary particulates. Particulate matter is measured in different ways: as total suspended particulates (TSP), particulate matter less than 10 μm in diameter (PM_{10}) or particulate matter less than 2.5 μm in diameter ($PM_{2.5}$). The emissions of $PM_{2.5}$ are the most harmful for human health. The secondary particulates are formed from the emissions of SO_2 and NO_x.

The difference in the results of particulate matter between the current situation and the future scenarios is remarkable (Fig. 6). In addition the improvements in reduction technologies also decrease the airborne $PM_{2.5}$ emissions in the future oil shale electricity production.

3.3.1.7. Depletion of oil shale, natural gas and uranium. The result for the impact category 'depletion of fuels' indicates that the use of oil shale is not as critical as other fuels (Fig. 7). The annual world consumption of oil shale is approximately 23 million tons in 2006, an estimation for the world resource is 10 billion tons. Consequently consumption/reserves is 2.3×10^{-6}.

The same ratio for natural gas is 0.015 (EIA, 2006) and, respectively, for uranium 0.014 (World Nuclear Association, 2006). Although the ratios are the same order of magnitude, less uranium is needed compared with natural gas to produce the same amount of energy, which explains the differences between 'natural gas and nuclear scenarios' in Fig. 7.

3.3.1.8. Significance of impact category indicator results. The normalisation results provide a better understanding of the relative proportion or magnitude of each impact category within a scenario and between scenarios (Fig. 8). In normalisation, the reference value of an impact category represented the impact category indicator results caused by all human activities in Europe in 2002 (Seppälä et al., 2006a).

The normalised values directly illustrate the relative importance of each impact category in the scenarios if it is assumed that impact categories have equal weighting factors. Although there is no consensus about the weights of impact categories, it can be said on the basis of different expert opinions (e.g. Seppälä, 1999) that the reduction of GHG is the top issue at the European level. The other impacts do not play as an important role as climate change. If the normalisation results in Fig. 8 are multiplied by impact category weights, the significance of climate change further increases compared with the other impact categories. It can be assumed that nowadays the reduction of European GHG is at least two times more important than the reduction of European acidifying emissions. Thus, on the basis of normalisation results it can be said that climate change is the most important impact category among characterised impact categories in all the scenarios, whereas tropospheric ozone formation is the least significant.

3.3.2. Results of other impacts

3.3.2.1. Human toxicity. In a study by Seppälä et al. (2006a) it was shown that heavy metals and other harmful toxic emissions caused by oil shale electricity production can be reduced in the future so that their impacts on human health corresponds to the impact level of emissions caused by current hard coal electricity production technology. However, on the basis of the inventory results obtained by the Ecoinvent database (Ecoinvent, 2004) current specific harmful emissions per 1 MW h caused by gas and nuclear power electricity productions are clearly lower than the emissions per 1 MW h caused by oil shale electricity production in 2020. Thus, it can be assumed that the difference between the scenarios based on human toxicity is caused by similar factors to the variation between scenarios seen in Fig. 5 based on ecotoxicity.

3.3.2.2. Land use. Activities related to mining change the land cover of large areas in both oil shale and uranium production. Ecosystems of large natural areas are

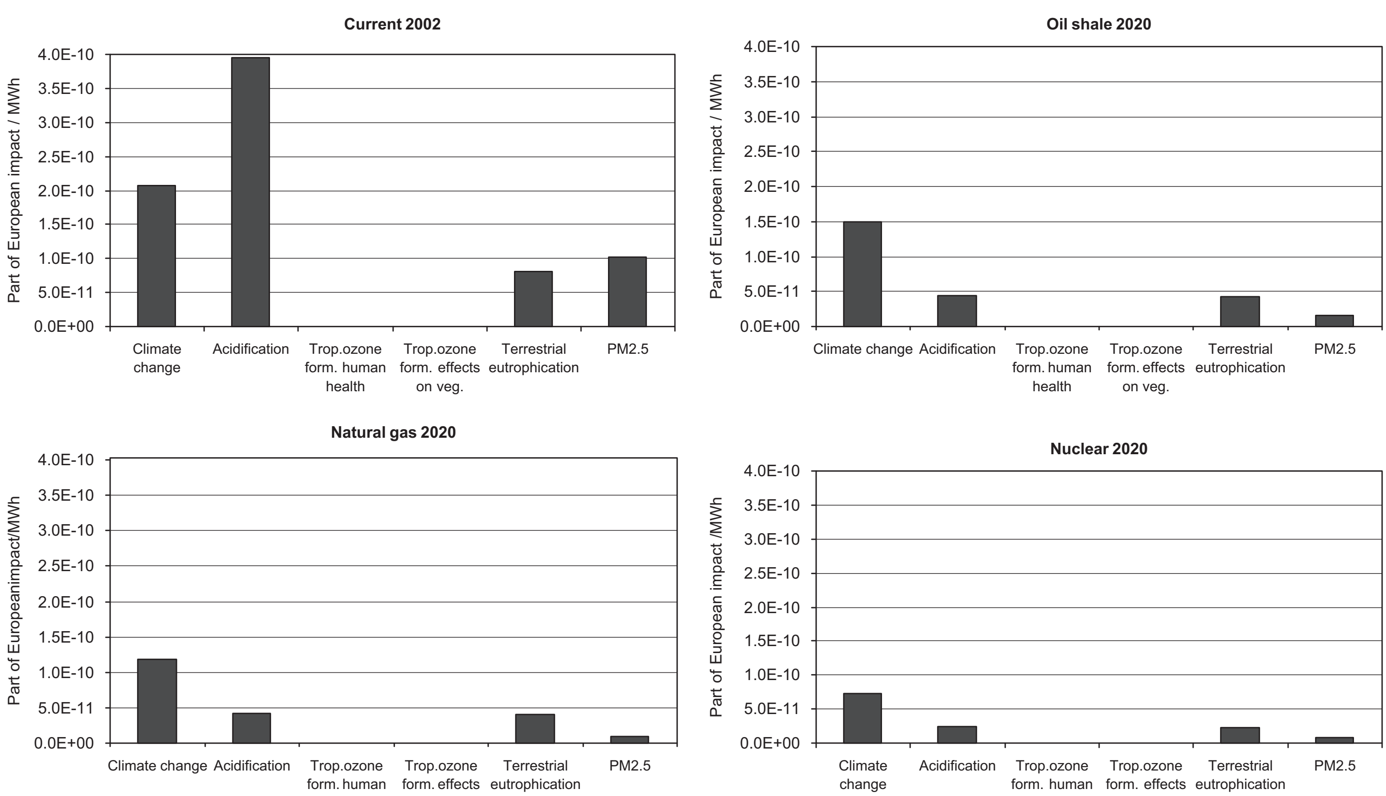

Fig. 8. Normalised values for the different impact categories. The values are calculated by dividing the impact category results of the scenarios by the European reference values.

destroyed and can never be restored. Extraction can cause surface subsidence when underground mining activities cease. Changes in hydrology and chemical composition of mine water can also be detected. Both oil shale and uranium are being extracted from open cast and underground mines. The effects of mining can go far beyond the small area disturbed in the operation. It requires the construction of roads and waste disposal areas.

The exploration and production of natural gas can also have a significant impact on the environment although nowadays new technologies have lessened them significantly. Natural gas deposits are being found at locations that are deeper underwater or underground, but several new drilling techniques do not require as much land as mining operations, and due to its gaseous form the waste disposal is insignificant.

The land occupation value for oil shale electricity production is nearly 5.8 m^2 year/MW h (Talve et al., 2005) and for nuclear power around 5.68 m^2 year/MW h (Ecoinvent, 2005). The land occupation value for natural gas electricity is between 0.5 and 0.6 m^2 year/MW h depending on the combustion technique and the transportation distances (Ecoinvent, 2005).

Regardless of the fuel, changes in the environmental conditions caused by the production stage have led to overall alteration of the natural vegetation structure. However, on the bases of the current data these local impacts are difficult to express per 1 MW h. For this reason, it is also difficult to say whether the land use related impacts are bigger in the context of the oil shale or nuclear power electricity.

3.3.2.3. Wastes. Oil shale electricity production causes a lot of wastes which mostly originate from the underground mining and the chemical composition of oil shale. The content of organic matter in the oil shale is only between 10% and 65% and the caloric value is very low, 8–10 MJ/kg (Gavrilova et al., 2005). The incombustible mineral matter in the oil shale is mostly limestone. The amount of waste rock in the oil shale mining per 1 MW h is almost equal to the amount of oil shale ash from the power generation (Seppälä et al., 2006a). The current ash removal system generates enormous amounts of liquid waste, which is classified as hazardous because of its high alkalinity. Also the leaching of elements from ash piles followed by infiltration into watercourses, groundwater and soil has a negative impact on the environment.

Nuclear mining also causes an extensive amount of waste rock. Additionally, nuclear mining releases radon gas and generates radioactive sludge from the enrichment process which can run into the environment. A high level of environmental protection is needed. Ash waste caused by nuclear power is absent, whereas nuclear electricity generates radioactive wastes. However, they do not cause harmful radiation impacts on the environment if safety systems work according to plan. For this reason, impacts related to radioactive waste are handled in the impact category of accidental releases (see below).

Due to its gaseous form, the impacts of waste generated from gas electricity production are insignificant compared with those of the wastes of oil shale and nuclear electricity. However, at this stage it is difficult to say what are the environmental impacts caused by waste management of different electricity production forms in 2020. In any case, on the basis of the information presented above the natural gas scenario can be ranked the best from a waste perspective.

3.3.2.4. Accidental releases. The probability of serious accidental releases from nuclear power plants causing radiation is extremely small, but due to the possible severe consequences the risk of accidental releases from nuclear power plants are treated very seriously by society. In addition, the safety of systems for the long term storage of radioactive wastes is a controversial issue. From the viewpoint of accidental releases the nuclear power scenario can clearly be ranked worst.

3.3.3. Ranking of scenarios

The characterisation results demonstrate the environmental performance of the different electricity supply scenarios in the context of the selected environmental impacts. From the viewpoint of these impacts on the environment the 'best' scenario appears to be the 'nuclear scenario', in which nuclear energy is the main energy source (almost half of the total) (Table 4). However, it should be noted that the best alternative depends on the weight or acceptance of accidental releases or other qualitatively defined impacts (Table 5). The natural gas scenario will be the best electricity production alternative if the weight of accidental releases is very high compared with the other impact category weights in the aggregation of impact category scores to final priorities or if the existence of radioactive threats cannot be tolerated.

Table 4
Comparison of the scenarios to 'Current 2002' based on characterisation results

Impact categories	Oil shale 2020	Natural gas 2020	Nuclear 2020
	Change (%)		
Climate change	−27.8	−43.1	−65.0
Acidification	−88.9	−89.5	−94.0
Tropospheric ozone formation (human health and vegetation)	Insignificant		
Aquatic eutrophication	−46.0	−46.6	−68.3
Terrestrial eutrophication	−47.6	−50.5	−72.3
Chronic aquatic ecotoxicity	−46.0	−78.4	−78.4
Chronic terrestrial ecotoxicity	−32.0	−72.9	−72.9
$PM_{2.5}$	−84.1	−91.0	−92.3
Depletion of fuels	+95.6	+513.2	+95.2

Table 5
Comparison of the scenarios to ‘Current 2002’ based on the expert judgment of the authors

Impact categories	Oil shale 2020	Natural gas 2020	Nuclear 2020
Human toxicity	Worst		
Waste related impacts		Best	
Land use related impacts		Best	
			Worst

4. Conclusions and future outlook

In this study, three different future electricity supply scenarios for Estonia were designed based on the strategic guidelines and main goals of the Government of Estonia. The scenarios were compared to the Estonian energy supply profile in 2002. The environmental performance of each scenario was defined on the basis of the life cycle impact assessment (LCIA) methodology.

The results indicate that the ‘oil shale scenario’ would be a slightly worse alternative than the ‘natural gas scenario’ even if the new technical solutions in oil shale electricity production could remarkably improve its environmental impact in the future. In particular, emissions causing acidification and eutrophication as well as emissions of particulate matter will be reduced in the renovated oil shale power plants.

At present and in the future, land use and waste disposal are crucial issues, particularly for oil shale and nuclear electricity production. However, the depletion of oil shale is not as critical an issue as the use of natural gas and uranium, because the oil shale reserve in relation to its consumption is large. According to the significance analysis of five impact categories (climate change, acidification, tropospheric ozone formation, terrestrial eutrophication and particulate matter), climate change is the most significant impact on the environment in all future scenarios.

On the basis of the environmental impact assessment, the ‘nuclear scenario’, with nuclear energy as the main energy source, would appear to have the least damaging effect on the environment. However, it should be noted that the best alternative depends on the weight or acceptance of accidental releases or other impacts not defined in this context.

The future electricity supply scenarios for Estonia are indicative and based on the information accessible today. However, the fact remains that the strategic development plans for Estonia’s energy and/or electricity production sector are subject to possible changes, depending on issues such as economic development and the international energy market. It can be expected that energy supply security, environmental sustainability and competitiveness will also be central objectives for Estonia’s energy policy in the near future as they are for EU energy policy (EEA, 2006).

The ‘oil shale scenario’ for electricity production insures that Estonia will remain self-sufficient in energy production which is according to Estonian energy policy. In addition, it seems that cleaner technology for oil shale electricity will reduce emissions in line with the requirements of the European Union’s directive on large combustion plants (2001/80/EC) by 2015. However, big questions remain concerning GHG emissions. On the basis of current knowledge, CO_2 emissions released form oil shale electricity production cannot be reduced using cost-effective technology. Although the Kyoto’s targets do not currently cause problems for Estonia (Estonian Environment Information Centre, 2005), CO_2 will likely become a more important issue for Estonia in the future. Due to increasing economic growth, Estonia will need additional electricity production capacity in the future. Taking into account the possible worldwide requirements for reducing CO_2 emissions in the near future it will be a significant advance to Estonia if this additional electricity can be produced from sources with low CO_2 emissions. For this reason, the increased use of renewable energy sources (biomass and wind energy), energy efficiency technologies and CHP (combined heat and power) could be attractive domestic alternatives compared to new nuclear and oil shale electricity production.

The utilisation of the results of this impact assessment conducted in this study depends on the weight of environmental issues in Estonian energy policy in the near future. Future decisions on the development of the Estonian energy sector are most likely based on technological, economical or political aspects. Political aspects are likely to be the most significant. However, this type of study can give additional value to the discussion due to the increasing role of sustainability in energy issues. In the future, there is especially a need to study electricity production scenarios in which the role of biomass and energy efficiency measures play a bigger part than in the scenarios of this study. This requires new LCA-based data on the environmental issues, energy production/saving potentials and the costs of biomass energy and energy efficiency.

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