Economics of Greenhouse Gas Limitations

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Foreword

This is the final report of the Estonian Country Case Study on Economics of Greenhouse Gases Limitations - Phase I: Establishment of a Methodological Framework for Climate Change Mitigation Assessment initiated by United Nations Environment Programme and granted by Global Environment Facility. The project is fully described in the project document GF/200-96-15.

The Estonian Country Study was carried out by the Executing Agency - Stockholm Environment Institute Tallinn Centre. The agency responsible for the implementation of the project in Estonia was the Estonian Ministry of the Environment. The supporting organisation was UNEP Collaborating Centre on Energy and Environment (UCCEE), Risø National Laboratory, Denmark. The main national institutions to provide the technical assistance were the Department of Electrical Power Engineering, Thermal Engineering Department, Faculty of Economics and Business Administration and Estonian Institute of Economics of Tallinn Technical University, Estonian Energy Research Institute, Institute of Geography of the University of Tartu, The Hiiumaa Centre for the Biosphere Reserve of the West-Estonian Archipelago and Stockholm Environment Institute Tallinn Centre. Estonian study team members visited in the capacity of guest researchers the Lawrence Berkeley National Laboratory, Brookhaven National Laboratory, SEI-Boston Centre and Harvard Institute of International Development in the USA and The Netherlands Energy Research Foundation ECN. Close collaboration was established with researchers of UCCEE, who gave valuable methodological advice.

The Estonian Country Case Study concentrated on the energy sector. Estonia is in the process of intensive transition from a centrally planned to a market economy. The reforming of the whole economy, included the energy sector, is underway at present in Estonia, therefore the current situation is permanently changing. This in its turn complicates the overall characterisation of the situation and makes it difficult to have well founded basis for further forecasts and projections. However, the main lines of further development have been worked out in the governmental document "Long Term Development Plan for the Estonian Fuel and Energy Sector", which was adopted by the Parliament (Riigikogu) in February 1998.

The Estonian Country Case Study team has managed with the complicated task to analyse the most probable GHG mitigation options to be used for the period up till 2035. MARKAL and MARKAL-MACRO models were used to build up the energy system development scenarios and to analyse various GHG mitigation options. Two main scenarios, respectively with low and high GDP growth rates, were assumed for the present analysis. Also the impact of carbon tax on the choice of possible energy generation scenarios was studied with the help of the model. The results have been discussed in the context of future socio-economic and political restrictions.

Special attention was paid to the problems and prospects of using Estonian main energy resource - oil shale - for the production of electricity. New combustion technologies developed in Estonia allow reducing CO_2, SO_2 and NO_x emissions, which makes them highly important in the process of following the binding agreements of international treaties on pollution abatement. The technological mitigation options of GHG emissions have been handled thoroughly, as they are of great interest for Estonia following the requirements of the Kyoto conference. Additionally, renewable energy sources were discussed more thoroughly, particularly wind energy, as they pose significant interest in the future energy policy in Estonia. Finally, a brief macro-economic analysis to explain the possible growth scenarios, considering GHG mitigation control figures, has been undertaken.

The Estonian study team of 14 persons worked in close co-operation with the Estonian Ministry of the Environment, various Estonian authorities and research institutions during almost eighteen months. As a project co-ordinator and manager I would like to express my gratitude to my good colleagues who made this study happen. Two all-Estonian conferences were convened and a number of workshops and information distribution activities have been organised. The ideas, principal viewpoints and particular calculations are those of authors. The role of the project manager was to adjust, as far as possible, the different positions of authors. However, he cannot take the responsibility for statements, facts or opinions made by the contributors.

Hereby I would like to thank Jayant Sathaye and Steve Meyers from Lawrence Berkeley National Laboratory, USA, for their valuable comments on the interim report. I would also like to acknowledge helpful colleagues from the UNEP Collaborating Centre on Energy and Environment, Risø National Laboratory, John Christensen and Kirsten Halsnæs, who gave their kind advice in the course of the work. My special thanks are due to Robert Redlinger, who was the Estonian case study co-ordinator and with whom the collaboration ran smoothly during the whole project period.

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Tallinn, June 1998

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Executive Summary

Estonian economy has faced major changes since the beginning of the 1990s. For quite a short time period a transfer from a centrally planned economy to an open market has taken place. After a deep recession period production has been steadily increasing since 1995. Deep changes have been facilitated by the radical monetary reform and with corresponding liberalisation of the market.

The main characteristic of Estonian socio-economic conditions is that they have undergone significant changes. In the political life the most important event has been regaining of independence in August 1991. This enabled to arrange the country's socio-economy in accordance with its people's will. While the objective was set to establish a democratic free market economy, considerable changes had to be undertaken. This is well reflected in changes of various socio-economic indicators. Most important steps have been among others monetary reform, liberalisation of prices, privatisation etc.

The monetary reform, executed in June 1992, allowed separation of the Estonian fiscal system from the so-called rouble zone. Estonian currency, the Eesti kroon (EEK), was introduced then. The currency is pegged to the German mark with a fixed exchange rate (1 DEM equals 8 EEK). The exchange rate has not changed over the years and has provided therefore security for investors. Being less vulnerable to the fiscal changes in the rouble zone, the national currency system has allowed Estonia to develop business towards Western countries. Within the Estonian context this, in turn, allowed faster reduction of inflation rates than in the Commonwealth of Independent States (CIS).

Price liberalisation is essential to integrate the market into the global open market. In order to achieve openness of market, Estonia has removed barriers restricting trade, abolished fixed prices, deregulated the markets, etc. There are currently only a few areas where prices are regulated by the state. Liberalisation has caused high inflation rates, which were higher at the beginning, but are still considerably high (over 10%) even today. While the process of convergence demands time inflation is supposed to remain around 10%.

Privatisation of Estonian enterprises has been almost completed. There are only large infrastructure companies to be privatised. As those are monopolistic in the market and/or of strategically important their privatisation is more time consuming.

Transition from highly centrally planned Soviet type of economy to a free liberalised economy has caused a significant decrease in the gross domestic product, which fell constantly up to the year 1994. GDP growth rates obtained positive values only since 1995. Since then the GDP has turned into a growth pattern and this is expected to be a continuous trend. By 1997 the GDP growth rate reached 11%, which is actually one of the highest growth rates amongst the countries with economies in transition. The structural contribution to the GDP has also been changing over the time.

One of the most distinguished processes has been a decline of the agricultural sector. The decline of the industrial sector in general has been expectedly long. This is because investments into production provide a positive effect later than the same investments made into the service sector. The latter is less dependent on investments. That is also one reason why the increase in the service sector has been the highest. Another reason for the increase has been the earlier low profile, which made a better basis for growth. Among industrial sectors Estonia depends on its traditional sectors like food, timber and furniture, chemicals, and power engineering. Those industries have undergone modernisation, which is reflected in improving product quality. Estonian exports to the Western markets have been increasing gradually and today major export partners are those from Western Europe, especially Scandinavian countries.

Estonian trade balance has been negative since 1993. This means that imports have exceeded exports. Among other factors this is caused by the smallness of the country where not everything can be produced locally and therefore the majority of goods have to be imported.

During past decades the energy sector has been one of the key sectors in economic development in Estonia. The development of the energy sector has been identified as a strategic component in the stable development towards a market economy. As a factor of production, energy contributes significantly to the development of all other sectors. From the point of view of Estonia's total emission of greenhouse gases, the energy sector is contributing the biggest share. Therefore this sector was selected for a thorough study of the GHG mitigation options in the frame of the present country case study. During centrally planned economy the intensive energy production was based on oil shale. This has been the main reason why Estonia was accounted amongst the world's biggest per capita GHG emitters till the 1990s.

As the oil shale based power generation is the biggest source of GHG, the ways to reduce the total emission of GHG are of high priority in implementing the obligations of UN Framework Convention of Climate Change. In the present work quite an essential emphasis is on the various technological aspects of the firing of oil shale. As the oil shale based electricity production has a long history since the 1920s in Estonia firing technologies have been continuously developed and a good know how basis has been created by Estonian scientists in this specific field of oil shale combustion. New approaches to combustion allow significant reduction of both the GHG and sulphur dioxide emissions. The latter has been one of the most problematic pollutants for Estonia, as the damages from sulphur dioxide emissions are well defined. Besides, sulphur dioxide reaches the neighbouring Finnish territory causing harm to environment.

In June 1993 Estonia and Finland signed a bilateral agreement on reducing the emissions of sulphur according to which Estonia must reduce its SO_2 emissions by 80% by 2005 from the 1980 level. The NO_x emissions are not allowed to exceed the 1987 level.

Oil shale is the most important domestic fuel for the Republic of Estonia. In 1996 the total primary energy supply was 226 PJ. Oil shale production was in the same year 138.8 PJ and its share in the Estonian energy balance was 59.1%. Each year some amount of oil shale has been also imported from Russia. Active oil shale deposit resources are approximately 1.2–1.3 Gt and passive resources are about 4 Gt. Nowadays oil shale is produced at six underground mines and four open pit mines. The net electricity production in Estonia was 6.3 TW·h in 1996. More than 98% of power is produced in four oil shale power plants with total electrical capacity 3060 MW. About 15% of heat production bases on oil shale combustion. The biggest electrical power plants are the Estonian power plant with total electrical capacity 1610 MW and the Baltic power plant with total electrical capacity 1390 MW. The oil shale consumption for power production was 13 Mt in 1996. The share of total emission of carbon dioxide from oil shale power plants constitutes 70–75% of total carbon dioxide emission in Estonia. Oil shale is used also for shale oil (synthetic crude oil) production and as a raw material for the chemical and cement industries.

As the CO_2 mitigation has a key role to follow the commitments of the Kyoto protocol, significant cutting of CO_2 emission by oil shale power plants is a highly important issue. Two parameter groups have a great influence on the specific emission of CO_2 (kg CO_2 per kW·h production of electricity) in a power plant. The first group is the conversion efficiency of fuel energy to electrical power (specific consumption of heat for the production of electricity (MJ/kW·h) determined from the power plant's net thermal efficiency. The second group of parameters depends on the properties of fuels burned in the power plant, but especially on the carbon content and carbon conversion extent to CO_2.

Oil shale will be the most likely energy source for Estonia to be used in the future. Therefore, the GHG mitigation options in the use of oil shale combustion technologies have a key role to play here. Presently the high-temperature pulverised firing technology (PF) is used in oil shale fired power plants in Estonia. The boilers used in power plants have been specially designed for Estonian oil shale. The PF technique for burning oil shale is characterised by very intensive fouling of the heat transfer surfaces of the boiler with ash deposits and high-temperature corrosion. Because of intensive high-temperature corrosion of the metal of superheater heat transfer surfaces the superheated and reheated steam temperatures are low and the net average efficiency of oil shale power plants is 0.27–0.29.

Estonian oil shale belongs to the carbonate class of fuels. The carbon present in oil shale is divided into two parts – organic and mineral carbon. The organic carbon is bound with organic matter molecule of oil shale and goes mostly into combustion products as CO_2 irrespective of the fuel combustion technology. The mineral carbon is bound with inorganic matter of oil shale and occurs as mineral CO_2 in carbonates' minerals - mainly with calcium carbonate (calcite) and partly as dolomite. At the combustion of oil shale the formed of CO_2 is divided into two parts - organic CO_2, which generates from organic carbon in the oxidising process, and mineral CO_2, which is formed in carbonates minerals' decomposition processes. The organic and mineral CO_2 concentration in the combustion products of oil shale depends on the organic and mineral carbon content in the fuel. CO_2 concentration in combustion products formed from the organic carbon of oil shale is very slightly affected by the fuel combustion technology but the fuel combustion technology has a very remarkable influence on the amount of the CO_2 emitted from carbonate minerals.

The CO_2 pressure in the combustion products plays a great role in carbonates behaviour in the combustion processes. In the existing oil shale power plants using the PF combustion technique at atmospheric pressure the CO_2 pressure in the combustion products is the range 0.014-0.016 MPa. This is lower than CO_2 equilibrium pressure for thermal dissociation of calcium carbonate, and thermal dissociation of carbonates is possible. The carbonate minerals' decomposition rate in case of the PF technology is in the range 0.96-0.99. Proceeding from the annual average proximate composition of oil shale (LHV as received basis 8.3-8.4 MJ/kg) the specific emission of CO_2 (kg CO_2 per kg oil shale) is 0.90-0.91 kg/kg or 1.35-1.39 kg/kW·h of electric power produced. The total emission of the CO_2 from oil shale power plants was approximately 12.5 Mt in 1996. Also, this would raise the exploitation and maintenance costs of the power plant.

Oil shale power plants have a comparatively high emission of sulphur dioxide in spite of the high binding capacity of sulphur dioxide by ash in the gas passes of the boilers. Approximately 15-20% of the total sulphur in oil shale goes into stack as SO_2. Sulphur dioxide emission can be radically reduced using the PF technology with gas-cleaning devices. This solution is not realistic due to high cost of the devices. Moreover, the working life of new cleaning equipment will probably be considerably longer than that of the existing boilers.

The low-temperature fluidised bed combustion (FBC) technology of solid fuels is a modern technique. This technique is divided into atmospheric and pressurised combustion technology.

The FBC technology is usually classified as either bubbling (BFBC) or circulating fluidised bed (CFBC). In BFBC the air velocity in the combustor is low and the particles behave like a boiling fluid and stay in bed. In such a system heat exchanger tubes immersed within the bed particles are usually used. In CFBC the air velocity is higher and much material leaves the bed and is collected by cyclone separators. Due to very low fuel concentration in the combustor and the high thermal capacity of the solid phase there is no need for tubes of heat transfer surfaces in the bed. The water wall tubes cool the upper part of the combustor. In modern atmospheric CFBC boilers the fluidised bed heat exchanger (FBHE) is used. The FBHE is a bubbling bed heat exchanger fluidising by air. Using the atmospheric CFBC technology all the sulphur in oil shale will be captured with ash and the use of the gas cleaning equipment is not necessary.

The pressurised fluidised bed (PFBC) combined-cycle technology is a top combustion technique. The system is a combination on Brayton and Rankine power cycles. Such a combined energy conversion system has a gas turbine in the open cycle and a steam turbine in the closed cycle. The main element in the PFBC system is the fluidised bed boiler placed into the steel pressurised vessel. The heat transfer surfaces are located in the fluidised bed. The boiler operates at a pressure 1.2-1.6 MPa. The combustion temperature is usually in the range 800-900^{0}C. The gas turbine compressor supplies gas to the pressurised vessel that contains a bubbling fluidised bed. The bed contains heat exchanger tubes. The pressurised flue gas exiting the combustor is cleaned of solid particles in a cyclone system or in ceramic filters. The gases then expand in a gas turbine and generate additional energy and then pass through a heat exchanger to preheat feed water for the steam cycle before being discharged to the atmosphere. The gas turbine drives a compressor and the electrical power generator.

In the pressurised FBC combustion conditions all the sulphur in oil shale is captured with ash. This is of great value from the point of view of reduction of sulphur emissions, particularly following the requirements of abatement quotas according to a bilateral agreement with neighbouring Finland.

One perspective technique for oil shale power plants is introducing the PFBC combustion technology. The PFBC technique has many advantages compared with PF burning technologies from the air pollution point of view. In the pressurised combustion conditions CO_2 pressure in the combustion products is in the range 0.14-0.16 MPa, which is higher than CO_2 equilibrium pressure for thermal dissociation of calcium carbonate, and thermal dissociation of carbonates is not possible. In spite of the impossibility of thermal dissociation of carbonates their decomposition to some extent occurs due to reactions between oxides in carbonates, sulphur dioxide and sandy-clay minerals. The carbonate minerals' decomposition rate using oil shale PFBC technology is in the range 0.25-0.40. Burning oil shale in PFBC with net LHV 7.5-8.5 MJ/kg the CO_2 concentration in combustion products decreases by approximately 13-20% and the heating value of oil shale increases 5.5-8.0% compared with atmospheric combustion conditions. Proceeding from the annual average proximate composition of oil shale (LHV as received basis 8.3-8.4 MJ/kg) the specific emission of CO_2 by using PFBC techniques is in the range 0.81-0.82 kg/kg or 0.77-0.83 kg/kW·h.

CO_2 specific emission by using the PFBC technology decreases 40-44% compared to the PF technique.

The total emission of CO_2 falls when the PFBC technology is used to 7-7.5 Mt/yr. (in 1996 12.5 Mt). In case of the PFBC technology of oil shale combustion the sulphur dioxide concentration in the flue gas is approximately zero. This is highly important from the point of view of the general pollution abatement policy. The content of nitrogen oxides in the flue gas decreased 15-20% compared with the PF technology.

The figures presented above show the ultimate importance of oil shale combustion technology change for the reduction of all emissions from Estonian oil shale based power sector. Compared to the present pulverised combustion, the CO_2 emissions could be reduced up to 44%, the NO_X emissions up to 20% and SO_2 emissions could be totally avoided.

Besides oil shale Estonia has other domestic primary fuel resources of peat and wood, also waste products from forest as well as secondary fuel resources of shale oil. Estonian main renewable energy sources suitable for commercial energy production are wood, wind and water. At the same time Estonia lacks natural gas, oil and coal, those fuels have to be purchased at world market price level. Due to the shift to European prices of energy carriers Estonian primary energy supply has changed towards the increase of domestic fuels. For example, the share of oil shale has increased from 58% in 1990 to 63% in 1996. The share of wood and peat had reached 9% level to year 1996 as against 3% in 1990. The share of imported fuel oils dropped from 18% in 1990 to 5% in 1996. The share of domestic fuels in the primary energy supply is presently about 70%.

Approximately 48% of Estonia's territory is covered with forest and shrubbery. It is possible to get 4–4.5 Mm^3 fuel from Estonian forests, which is equivalent to 26–30 PJ primary energy. In 1996 the use of biofuel (mostly wood) as a renewable energy was 2.1 Mm^3, which accounted for about 10% of the production of primary fuels in Estonia. This figure is showing a clear tendency towards growth.

Peat fuels, including peat briquettes, make up about 4% of the primary fuels produced in Estonia. In 1996 a total of 0.53 Mt peat fuels was produced. Of the territory of Estonia approximately 22% is covered with wetlands. The reserves of peat are estimated at 2.4 Gt. Peat resources can be treated as renewable only with certain reservations because of their slow recovering. The recovering rate is approximately 1 mm/yr. which is equivalent to 0.8 Mt. As the consumption of peat does not surpass its increment, it could be defined as a renewable energy.

Estonia has considerable wind energy resources, especially in coastal areas. As a maximum 0.3 TW·h of electricity could be produced annually without conflicting with other requirements. For this, 120 MW of wind turbines should be installed in regions with good wind conditions. Because of high capital costs the price of wind generated electricity will be rather high compared with the relatively low price of electricity generated on the basis of oil shale. This is presently the main obstacle to harnessing wind energy. In June 1998 Riigikogu decided to amend the Estonian Energy Act, which involves obligation to buy wind generated electricity by public grid at preferred price level. This will help overcome the obstacle posed by low price.

The amount of hydro energy is very limited due to the generally flat surface of the country. As maximum 30 MW hydropower can be installed and only a few former power plants with a total capacity of 4–5 MW can be restored in the near future.

Rough estimations show that every kW·h of electricity produced by wind or hydropower instead of pulverised combustion of oil shale in existing power plants will avoid the emission of 1350 g CO_2, 10 g fly ash, 1 g NO_x and 9 g SO_2.

The only considerable application of solar energy in the future could be for water heating in summer.

At present a reasonable part of the available renewable energy sources is in use. Wood and peat are predominantly used for the production of heat, though peat is beginning to be burned also for electricity generation. In 1996 about 15 PJ firewood and wood chips were produced and 5.1 PJ of peat was used in the energy sector. In 1996 wood and peat accounted already for 9% of the primary energy supply. At present five small hydro power plants with a total capacity of 760 kW are in operation, and the first wind turbine for commercial energy production with a capacity of 150 kW has been operating since September 1997. As there is no domestic industry producing hydro or wind turbines most of the equipment has to be imported. After a successful start also domestic production of wind turbines could be considered.

Thanks to increasing use of waste wood in the energy sector domestic production of equipment for biomass boilers has started and is rapidly developing.

Wood and peat are usually burned at boiler houses where the most common fuel used to be crude oil, coal or natural gas. Therefore the reduction in the emission of air pollutants is somewhat lower than for oil shale power plants. Wood or peat is economically feasible to use only if the fuel is located closer to the boiler house than 50–100 km. In Estonia good prospects for wood and peat combustion are in the southern part of the country where smaller towns, extensive peat bogs and large forests are situated. Still, wood and peat differ from each other in the content of pollutants emitted. For peat the CO_2 cycle is long and its emission is taking place both during excavation (beginning with drainage) and combustion. However, SO_2 and NOx emission can be kept on a relatively low level and their emission can be significantly reduced compared to fuel oil or coal combustion. In case of wood combustion the emitted CO_2 will be quickly used during photosynthesis. NO_X and especially SO_2 emission can be kept low as the sulphur content in wood is low. If wood and peat are used also for electricity generation the potential reduction in GHG emission will be even bigger.

Wood and peat have been winning more and more popularity, particularly during recent years. In the longer prospective it has been foreseen by the government to increase the share of peat, wood and wind energy from the present 9% to 13% to the year 2010. Renewable energy resources are considered to give no CO_2 emissions since they have no impact on the global carbon cycle.

The analysis and planning of the energy system development, which are closely related to the changes in the whole economy and environmental limitations, require a large and sufficiently detailed mathematical model capable to describe the energy sector as a whole and enabling to "play through" various development strategies.

Energy system modelling and GHG emissions analysis using the MARKAL and MARKAL-MACRO models have been an important part of the present study of selecting mitigation options for Estonia. To model the energy system development and to analyse the resulting CO_2 emissions a demand-driven, multi-period linear programming model of the technical energy system MARKAL and MARKAL-

MACRO, the hard-linked model of MARKAL and MACRO economic model, were used.

The year 1995 was chosen as the base year for model calculations and the planning horizon was taken 40 years, which in turn was divided into 5-year periods. It was assumed that Estonian population will not grow, long-term discount rate is 0.06, there are no limits on fuel import and investments and electricity import will be restricted. Social and political constraints could not be considered because their actual values were unknown.

It was assumed in all scenarios considered that Estonia fulfils targets of international agreements on CO_2, SO_2 and NO_X emissions. Those agreements constitute that Estonia must reduce its SO_2 emissions by 50% by 1997 and by 80% by 2005 from the 1980 level. The NO_X emissions are not allowed to exceed the 1987 level. According to the Kyoto agreement Estonia's CO_2 emissions in 2010 must be at least 8% lower than in 1990.

The economic development of Estonia depends to a large extent on different directions of the integration process of Estonia with other groups of countries like the EU, the Baltic states, Russia and the Commonwealth of Independent States (CIS). The integration of Estonia will be mainly influenced by Estonia's future role in its economic space connected with the West and the East. To cope with these uncertain developments, two different energy demand projections were developed.

The scenario with modest economic growth forecast in combination with fulfilment of present environmental agreements was decided to serve as the baseline scenario for the current project.

The baseline scenario assumes Estonia's close integration with Western political and economic structures, especially with the EU, while relations with Russia and other CIS countries are relatively weak. Under this scenario, the GDP is expected to grow, in average, 2.5% annually during 1995-2035. The service sector will be of greater importance and the share of manufacturing will decrease further. Estonia will not have wider access to Russian market under the conditions of the baseline scenario and this will diminish incentives of large international companies to invest into Estonia. The Scandinavian foreign investments will be dominating and influence the structure of Estonian economy. The useful energy demand is expected to grow from 76 MJ/capita in 1995 to 121 MJ/capita in the year 2030.

The optimistic scenario assumes that Estonia's market is oriented towards both the West and the East. The flows of transit goods and services and related services will have a greater role in the economy. The closer relationships with the CIS markets will attract into Estonia more large international corporations and foreign investments of those companies will have an increasing role in the Estonian economy. Under this scenario, the average annual GDP growth will be 5.3%. The useful energy demand capita is expected to grow from 76 MJ/capita in 1995 to 168 MJ/capita in the year 2030.

Demand projections were developed for industry & agriculture, residential & commercial and transport sectors of the economy, and for non-energy use of fuels. The main industrial energy consumers are the chemical industry, other non-metallic mineral products, food industry, mining and fuels. The faster growth of those industries in the second scenario is related to wider use of Russian inputs (a new methanol plant using imported gas is a possible new production unit in this scenario).

The establishment of a new paper plant and the respective increase in energy demand have been assumed in both scenarios.

GHG emissions can be reduced by changes in both supply and consumer sides of the energy system. Supply side GHG mitigation options for Estonia are:

- Change of fuels, especially reducing the share of oil shale in electricity production
- New clean and efficient fossil conversion technologies
- Larger use of CHP
- Wider use of renewables
- Possible introduction of nuclear power
- Reduction of grid losses of heat and electricity.

Those options are modelled in MARKAL by describing the technical, cost, availability and environmental data of the corresponding technologies.

The main consumer side mitigation option is energy conservation.

Considering that MARKAL is an optimising model, already the baseline scenario is a mitigation scenario compared with the base year situation. It gives the optimal fuel and technology mix, and resulting emissions that correspond to the baseline assumptions. Moreover, several mitigation options like some low-cost energy conservation measures and reduction of losses were already accounted in developing energy demand projections. In reality, the optimal solution can be hardly followed and it can be considered as an energy policy target.

To investigate measures of GHG reduction not considered in the baseline scenario, special mitigation scenarios must be developed. In designing and modelling the special mitigation scenarios two different approaches were used:

1. Economic approach, when general assumptions and cost data are changed (e.g. introduction of environmental taxes, emission constraints, subsidies for some technologies, change of fuel price projections, etc.). In that case the model finds optimal (least cost) solution under new assumptions and we can find out from the results which changes will take place in the energy system (The Integrated Systems Approach).
2. Forced introduction of technologies that do not appear in the optimal solution or whose market penetration is too small under the assumptions made (The Partial Solution Approach).

Four mitigation scenarios were considered in the MARKAL modelling under this project:

- Low CO_2 tax case - Scenario with low CO_2 tax (4 US$/tonne of CO_2 starting from 2005).
- High CO_2 tax case - Scenario with high CO_2 tax (4 US$/tonne of CO_2 from 2005 and 20 US$/tonne of CO_2 after 2015).
- All high taxes case - Scenario with high CO_2 tax combined with high externalities on SO_2 and NO_X.

- Expensive oil shale case - Scenario where the oil shale price projection rises due to special taxes and increased mining costs over competitive with other fuels level. In principal, this is an oil shale phase-out scenario.

All mitigation scenarios were applied to both baseline and high growth demand scenarios.

On the basis of MARKAL results the following main conclusions can be drawn:

1. Total Primary Energy Requirements (TPER) will remain almost stable until 2005 and then grow very modestly due to substantial decoupling between economic output and demands for energy services, reinforced by increasingly efficient energy conversion systems. The share of oil shale will decrease significantly. A higher price and implementation of climate policies pose the most serious threat for oil shale. Imports of oil products (mainly for transport) and natural gas (for CHP plants, DH boilers, industry and residential and commercial use) will rise. The demand for gas will be increased by additional environmental actions.

   Other domestic resources - peat and wood are attractive in most scenarios. Peat use is vulnerable for more ambitious environmental goals. Wood will be an energy source also for a new pulp and paper mill.

2. Electricity production

   - Under the base case conditions oil shale based power production will continue to be the major electricity supplier through reconstructed units of existing power plants.
   - Reconstruction of part of conventional oil shale power plants to CFB combustion is a robust option appearing in all scenarios examined. If the O&M costs of PFBC units could be lowered ca 30% compared with the baseline assumptions, CFBC and PFBC reconstruction of existing oil shale power stations would become equally attractive already under the base-case scenario and PFBC technology would be preferred under high environmental taxes. Building of new oil shale power plants will appear far less attractive.
   - The amount of natural gas power (CHP, condensing combined cycle and gas turbines to meet the peak requirements) will increase significantly.
   - Gas fired CHP units offer the best prospects for combined heat and power production in all scenarios considered. Peat fired CHP is favoured in scenarios without CO_2 tax.
   - On the long term, coal and nuclear power plants offer the best prospects to replace oil shale electricity generation. Nuclear power will be favoured only when the highest environmental standards are considered.
   - Except for the own production of electricity and steam from black liquor in a new paper mill, non-fossil power production (hydro, wind) will remain negligible.

3. Heat production

   - In the base year the total district heat production is dominated by boilers, both large ones feeding extensive distribution grids and smaller ones feeding local systems.

- Total heat demand will decrease ca 10% during 1995-2000 and then it will remain almost constant.
- The share of boilers in the total production is expected to decline.
- Natural gas fired CHP units are the strongly preferred option for larger district heating systems and wood boilers expand for smaller schemes.
- On longer term peat CHP looks attractive also, but it appears to be vulnerable for charging of high SO_2, NO_X externalities and CO_2 taxes.
- Natural gas will be favoured also as fuel for individual boilers, where available.

4. Energy costs

- Energy system costs comprise all the costs made in the energy system: import and domestic fuel costs, production costs (capital, operation and maintenance costs), transport and distribution costs. Tax revenues are treated separately. Although they constitute a cost for energy consumers, they are not "real" cost on the macro-economic level.
- Despite the fast energy intensity improvements, total costs of the energy sector rise faster than TPER. This is on the one hand due to rising prices for domestic and foreign energy supplies and on the other hand to capital required for new investments. Consequently energy prices will have to rise.
- Required investments only in power plants until 2015 are some 13 billion EEK_{1995} (about 1 billion US$) in the case of baseline demand and 16-18 bllion EEK_{1995} in the case of high demand growth. Current tariffs appear insufficient to build up financial reserves for this purpose.
- Expenditures on fuels will shift from domestic to imported flows. This trend is stronger if more rigid environmental policies will be applied.
- Total energy system cost constituted ca 25% of the GDP in 1995, which is a typical level for economies in transition. Under the baseline economic development the Total System Cost/GDP ratio decreases only to 20% at the end of the planning period. In the case of optimistic economic development this ratio will decrease to 12% in 2035.
- High energy system costs are affected by the current low level of GDP per capita, high energy intensity of GDP and high needs for heating due to cold climate combined with poor quality of buildings and district heating systems.
- Total system cost differences between scenarios with and without special CO_2 reduction measures are rather small. Old worn-out technologies must be replaced in the near future anyway and costs of new technologies used by models are quite similar.

5. Emissions

- New technologies, economically viable under base case conditions, help to ensure that sulphur and carbon emissions will fall below agreed targets. This means that baseline development considers only SO_2 and NO_X restrictions and that includes no special actions to reduce CO_2 are taken, is already GHG mitigation scenario.
- Only in the case of high economic growth, CO_2 emission will increase over 1995 level in the long run (except under high CO_2 tax). At the same time the emissions will stay well below the Kyoto Agreement target (32 Mt).

- The CO_2 tax levels tested affect strongly the relative competitiveness of power and heat generation and other energy options. CO_2 emissions could fall well below the base-case level.
- NO_X emissions from the transport sector will be an increasing environmental problem.

Marginal costs of CO_2 reduction were analysed with MARKAL in two ways:

1. Conventional approach (The Integrated Systems Approach), when the marginal cost of CO_2 reduction is the model input in the form of CO_2 tax and CO_2 reduction level can be found from the model results.
2. Forced introduction of technologies that do not appear in the optimal solution (The Partial Solution Approach). In this case cost analysis of each CO2 reduction option can be made by comparing the total system cost and emissions data of the baseline scenario with results of a mitigation scenario containing this particular option.

Using the conventional approach, the reduction of CO_2 is achieved due to changes in technology and fuel mix on both the supply and demand sides of the system. The changes that take place in the system when CO_2 tax rises are the following: the use of natural gas will increase; wood use will grow up to the sustainable limit; a nuclear power plant will be introduced, hydro and wind energy, high cost energy conservation measures, and even biomass CHP will become attractive.

When the CO_2 reduction possibilities were analysed using the approach of forced introduction of technologies, the measures using natural gas as well as restoration of small hydro plants were not considered as specific options because they were extensively introduced already under the baseline scenario.

The results show that most of the energy conservation measures should be implemented. The main problem here can be the arrangement of financing of those projects.

Large amounts of CO_2 emissions could be cut off by restricting electricity export and opening the import instead. This option still means that CO_2 could be emitted somewhere else and it will also affect the whole economy (state budget, foreign trade balance, energy prices etc.). Changes in electricity export-import should be regulated by market.

Estonian Energy Strategy, Long Term Development Plan for the Estonian Fuel and Energy Sector, and MARKAL baseline results all foresee the continuation of oil shale power engineering during a few decades, though not in the present volume. Considering that, replacing of CFBC reconstruction of existing power plants with PFBC reconstruction is the most attractive option in the energy conversion sector for the reduction of CO_2, but also other emissions in the short term.

In the long run, GHG emissions could be radically reduced by introducing nuclear power. This option needs besides economic considerations also a political decision.

Wind energy and small-scale biomass CHP along with some high cost conservation measures appear to be the most expensive measures of CO_2 reduction considered here.

Main conclusions from the investigation of the impact of CO_2 reduction measures on the Estonian energy system and national economy with MARKAL-MACRO model are the following:

- CO_2 reduction measures will rise energy prices compared with the baseline scenario so much that energy demand must decrease
- The higher the CO_2 tax is the more expensive reduction options will be used
- High energy prices, costly technologies and reduced demand cause the lowering of GDP compared with baseline development
- To follow the baseline GDP projection under mitigation scenarios the energy demand should be lower than projected initially (energy intensity of GDP must be reduced) or vice versa, to satisfy the initial demand projections under mitigation scenarios, the GDP must grow faster than projected.
- Model results show us an ideal least-cost solution under certain assumptions and restrictions that can serve as a direction for actual changes.

To conclude we could say that the lowered energy demand due to the economic decline and sharp rise in the fuel and energy prices as well as a decrease in electricity exports resulted in ca 45% reduction of CO_2 emissions during 1990-1993. For the same reasons, Estonia has been able to meet the requirements set in the agreements on SO_2 and NO_X emissions with no special measures or costs. To meet the more rigid SO_2 restrictions and growing energy consumption in the future, Estonia must invest in abatement and in new clean and efficient oil shale combustion technology. Measures to reduce SO_2 and NO_X emissions will indirectly reduce also CO_2. Along with the closing of old oil shale fired plants and growing electricity consumption, other fuels will be used. The increase in energy demand then should not be fast due to constantly rising prices and efficient energy use. The reduction of energy demand through energy conservation must have the highest priority in Estonian energy policy.

Our calculations show that the Kyoto Agreement level of CO_2 emissions will not be exceeded. Restricted availability of imported fuels and nuclear power or enabling large scale electricity import can change the results significantly. The results presented here can also change because the database is being improved.

The real development of Estonian economy in recent years has shown quite modest GDP growth in 1995 and 1996, but sharp increase (ca 10%) in 1997. During that time energy consumption has remained stable. From today's prospective the Base-case High Energy Demand scenario development of the energy system seems to be the most probable for the near future. Actual changes and decisions will be strongly (still unpredictably) affected by forthcoming privatisation of the power sector. Real actions will be also affected by their social costs and political considerations not accounted in the modelling. From the viewpoint of supply security and also national security, high dependence of the power and heating sector on natural gas (economically optimal under strict environmental restrictions and taxes) is not desirable until Estonia has only one gas supplier - Russia. Changes proposed in mitigation scenarios could be implemented only when Estonia has at least one more gas supplier. An increase in the share of imported fuels in the energy balance, which is especially strong under mitigation scenarios, could be restricted by the national foreign trade balance.

For the present study, the main macro-economic interest is the influence of different solutions on the foreign trade balance. The starting point for calculations is the year 1995. Then the share of the domestically produced primary energy was 61%, including oil shale (quite a large amount was imported also from Russia), wood and peat. The share of imported primary energy was 39%. Fuels created 3.7 billion EEK or 9.5% of Estonian imports in 1996. We assume that imports will increase at the same level with economic growth in the respective scenarios. As the price increases of imports and fuel have been considered to be equal, we used for calculations only real growth figures. The results according to the main scenarios and several other assumptions would have the following influence on foreign trade.

Base demand scenario without emission taxes will increase the share of fuels in imports up to 12% in 2005 and 9.2% in 2020. In the same scenario, due to changes of primary energy sources in low CO_2 tax case, the share of fuels in imports will be 16% in 2005 and 13.8% in 2020. In high the tax scenarios, the share of fuels will be respectively 19% and 15.8% in imports. The high demand growth scenario without emission taxes will increase the share of fuels in imports up to 13.9% in 2005 and 8.3% in 2020. In the same scenario, due to changes of primary energy sources in low CO_2 tax case the share of fuels in imports will be 10.3% in 2005 and 9.3% in 2020. In the high tax scenarios, the share of fuels will be respectively 16.2% and 8.9% in imports.

The wholesale value of electricity produced in Estonia was approximately 4 billion EEK in 1996. Accepting price and output growth scenarios presented in the framework of this research, the value of electricity would be around 10 billion EEK in 2010 without emission taxes. The source of carbon dioxide in Estonia is dominantly the energy system (more than 90% in 1996). On the other hand, oil shale based production of electricity is the main source of emission inside the energy system. The total sum of taxes paid in 2010 will create 7% of the value of electricity in the low CO_2 tax scenario and 19% in the high CO_2 tax scenario. Considering minimal changes in the electricity price and output between 2010 and 2015, the total amount of the taxes paid could reach 65% (all high taxes scenario) of the value of production in 2015.

The oil shale complex and oil shale based power engineering employ altogether close to 10000 persons (7000 of them in oil shale mines and 3000 in power plants). That figure makes up approximately 1.6% of Estonian total employment and is thus not very significant. If Estonia closed down those fields, unemployment would increase from 10% to 11.6%. On the other hand, oil shale mines and power stations are located in the very critical north-eastern part of Estonia where the potential of social and political tensions is high and unemployment exceeds the average figure of the country. In that region those employees account for approximately 15% of the labour force and by estimation approximately half of them would not find a new job in the case of closing down the respective industries. However, unemployment in Ida-Viru County would increase from 15% to 22-23%.

Considering the relatively extensive peat and wood stocks, low environmental hazard of their usage and possible positive influence on regional development, the rising share of those fuels in the primary energy balance could be discussed. Especially if the all high emission taxes scenario were followed, the renewable resources could be also economically efficient in comparison with oil shale in Estonia. On the other hand, the low tax scenario will postpone the introduction of alternative energy sources like wind and wood chips. According to the Estonian energy strategy, an official document adopted by the Riigikogu in February 1998, the amount of primary energy produced from such inputs will increase by 60% in 2010. The share of renewable resources will increase from 8% in 1996 to 13% in 2010. The more uniform regional development, one of the political imperatives of Estonian future economic policy, will support the use of renewable energy resources.

Socio-Economic Background and Energy Issues

1 Basic Country Information

Estonia is located in the Northern Hemisphere on the eastern coast of the Baltic Sea between 57°30′N and 59°40′N (see Figure 1). The total area of Estonia is 45,227 km^2 including the two larger islands, Saaremaa and Hiiumaa. The area is comparable with that of Denmark and The Netherlands. Estonia is a low country, its highest point reaches a mere 318 metres. It has a mosaic landscape with plains, hills and numerous lakes.

Figure 1 Estonia in Northern Europe

Larger lakes are Lake Peipsi (on the border with the Russian Federation) and Võrtsjärv in central Estonia. Hydrographically the whole territory lies within the Baltic Sea catchment area. The rivers are short. The longest is the Pärnu River, which is 144 km long.

Agricultural lands cover 25% of the territory. Forests and wooded areas make up about 44% of the territory. Mires (bogs, fens, swamps) account for 20% of the land area. Towns and urban areas cover only 2.4% of the territory, roads and infrastructure 0.9%.

Estonia has a moderate Atlantic-continental climate. It represents a transition zone from the maritime climate type to the continental one. In spite of its comparatively small territory climatic differences in Estonia are significant, especially during the colder season of the year. Generally the duration of snow cover is between 75 and 130 days. Weather conditions depend directly on the cyclonic activity in the Northern Atlantic.

Weather changes are frequent. Summers are warm and winters are mild. South-westerly and southerly winds are typical throughout the year. Annual rainfall averages 500–700 mm. The annual average temperature is 4–6°C. Temperature ranges from a monthly average of –6.6°C in February to 16.3°C in July. Temporal variability of meteorological features has been very high in Estonia. Spatial variability is demonstrated by the mean temperature in January, which varies from –2.5°C on the western coast of the island of Saaremaa up to –7.5°C in the coldest inland areas. The winter cover stays normally about three months.

Estonia regained independence on 20 August 1991. The Constitution established the principles of the rule of law. It recognises the principle of separate and balanced powers, the independence of the courts, and guarantees fundamental human rights and liberties according to universally recognised principles and norms.

Estonia is a democratic parliamentary republic wherein the supreme power is vested in the people. The people exercise the supreme power through citizens who have the right to vote by electing the Riigikogu (Parliament of the Republic of Estonia) and by participating in referendums. The Riigikogu is comprised of one hundred and one members. Executive power rests with the Government. The head of State of Estonia is the President of the Republic.

There are 46 towns, 11 town communities and 3,274 villages in Estonia. Administratively Estonia is divided into 15 counties, 198 municipalities and 46 towns. Since 1993 a single-tier self government system is active in Estonia. The local municipality and town governments are responsible for resolving and regulating local issues independently and in accordance with the law. State interests are represented in regions by respective county governments.

2 Economic background

In the current chapter on the general socio-economic background and the energy sector information is provided about developments between 1990 and 1997. The country team is of the opinion that this is a period within which it is possible to see changes in the economy. This is a period when the economy was diverted from a centrally planned system to a market oriented one. During the last few years the decline of the economy has been converted to a rise. However, there is too little information to make predictions and design trends for the longer term development.

The economic reform had started already at the end of the 1980s, before the actual independence was regained. Reforms have occurred in the whole economy and economy has been totally restructured. This caused an economic decline, which lasted until 1994. By today economy has revived and turned into the path of continuous growth.

Similarly to the other former socialist economies, the Estonian economy was characterised by a structure of relative prices significantly different from those in the developed countries. A large part of investments were also made by redistribution of funds within the state budget. The exchange rate of the Soviet rouble did not correspond to the actual prices. A large share of the foreign trade was made on the basis of barter transactions.

The fact that the Estonian economy was still part of the rouble zone after independence was regained was regarded as one of the most serious problems within the economy. Any price fluctuations in the Soviet Union, or later in the CIS (Commonwealth of

Independent States), affected directly the Estonian economy. Rises in the prices on fuels and raw materials were reflected in rising prices in Estonia. Liberalisation of most of the prices that used to be regulated resulted in increased inflation. The highest inflation was in 1992 (see also Table 3).

Estonia conducted a monetary reform in June 1992. The currency board arrangement and convertibility of the Estonian kroon (EEK) were introduced. Since then the Estonian kroon is pegged to the German Mark (DEM) with the exchange rate 1 DEM = 8 EEK. The exchange rates to other currencies are calculated according to the DEM.

After a long period of drastically decreasing GDP (by 14% in 1991 and 15% in 1992) the Estonian economy started to revive in April 1993. During the 3rd quarter of 1993 the GDP increased for the first time. In 1997 the GDP increased by 11.4% (Table 1).

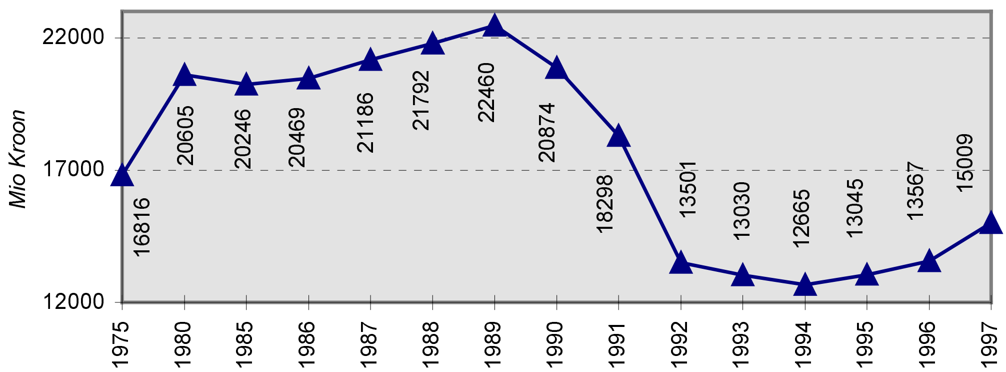
Table 1 GDP's growth rate compared to the previous year (Bank of Estonia, 1997-1998)

	1991	1992	1993	1994	1995	1996	1997
Growth %	–14	–15	–6.7	–1.8	+4.3	+4	+11.4

The Ministry of Finance has provided a medium term prognosis for further development of Estonian economy up to the year 2001 which envisages the growth of the economy. According to the Ministry the growth of economy in 1998 will be 5.5 % and in the following years 6% (Ministry of Finance, 1998). Those figures support the high growth scenario used in MARKAL modelling (Chapter 5).

The development of GDP in absolute figures at 1992 prices is given in Figure 2.

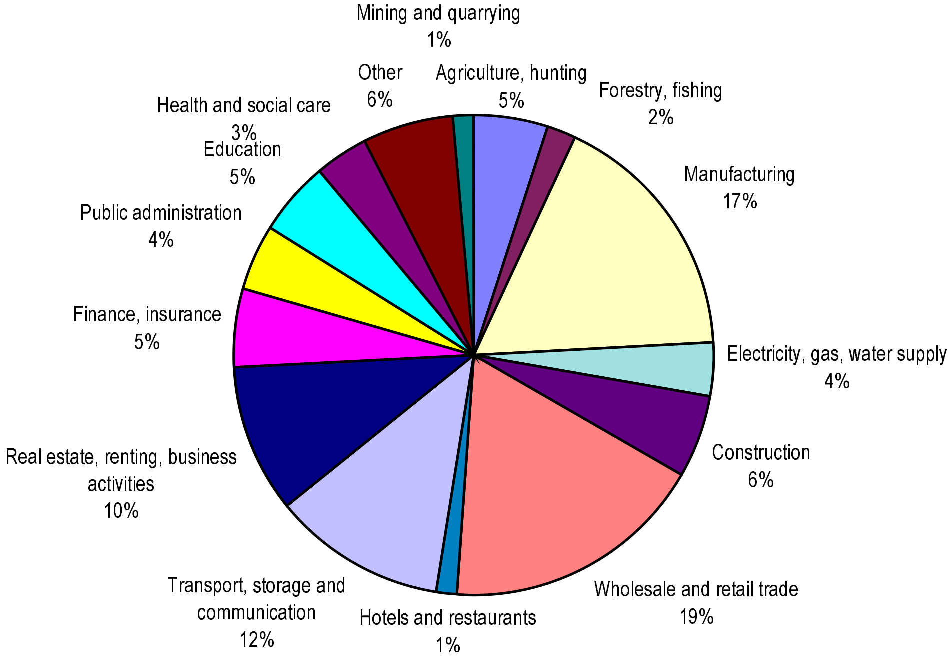
Figure 2 Development of GDP at 1992 constant prices



Among the other most influential factors supporting changes privatisation is worth special mentioning. By 1998, most of agriculture, production and housing had been privatised. The larger enterprises still to be privatised are those of infrastructure and natural monopolies like water and energy supplies.

Changes have occurred in the structure of fields of activity and in production. Traditional sectors have lost or are loosing their position. The role of traditional industrial and agricultural sectors in the national economy is diminishing, whilst new sectors – financial services, transportation, information technology – are rapidly growing. Changes in technology, globalisation, information technology support further growth of the Estonian economy. Sectoral contribution to the GDP in 1997 is depicted in the Figure 3.

Figure 3 Sectoral contribution to the GDP in 1997



Structural changes are continuing in the economy. Almost all sectors have been growing since 1994. Agriculture, which fell steadily since the beginning of 1992, is the only exception. According to the latest data the decline of agriculture has stopped also and during 1997 the first time a rise occurred. Some decrease can be observed also in the hotels and restaurants sector. A rapid development is taking s place in transport, trade and services as well as in forestry and wood processing Table 2.

Table 2 GDP by kind of activities, 1994–1996 (million EEK) at 1993 constant prices

Field of activity	**1994**	**1995**	**1996**
Agriculture, hunting	1600	1565	1499
Forestry	254	326	359
Fishing	113	137	165
Mining and quarrying	345	337	347
Manufacturing	3628	3813	3819
Electricity, gas, water supply	709	675	706
Construction	1258	1324	1455
Wholesale and retail trade	3475	3750	3960
Hotels and restaurants	275	264	263
Transport, storage and communication	2396	2405	2738
Real estate, renting, business activities	1403	1588	1609
Finance, insurance	589	596	644
Public administration	688	696	697
Education	1138	1174	1173
Health and social care	513	512	506
Other	1019	1073	1173
Total at basic prices	**19402**	**20232**	**21113**
Net taxes	2262	2353	2375
Total at market prices	**21664**	**22585**	**23488**

Source: Bank of Estonia, 1997.

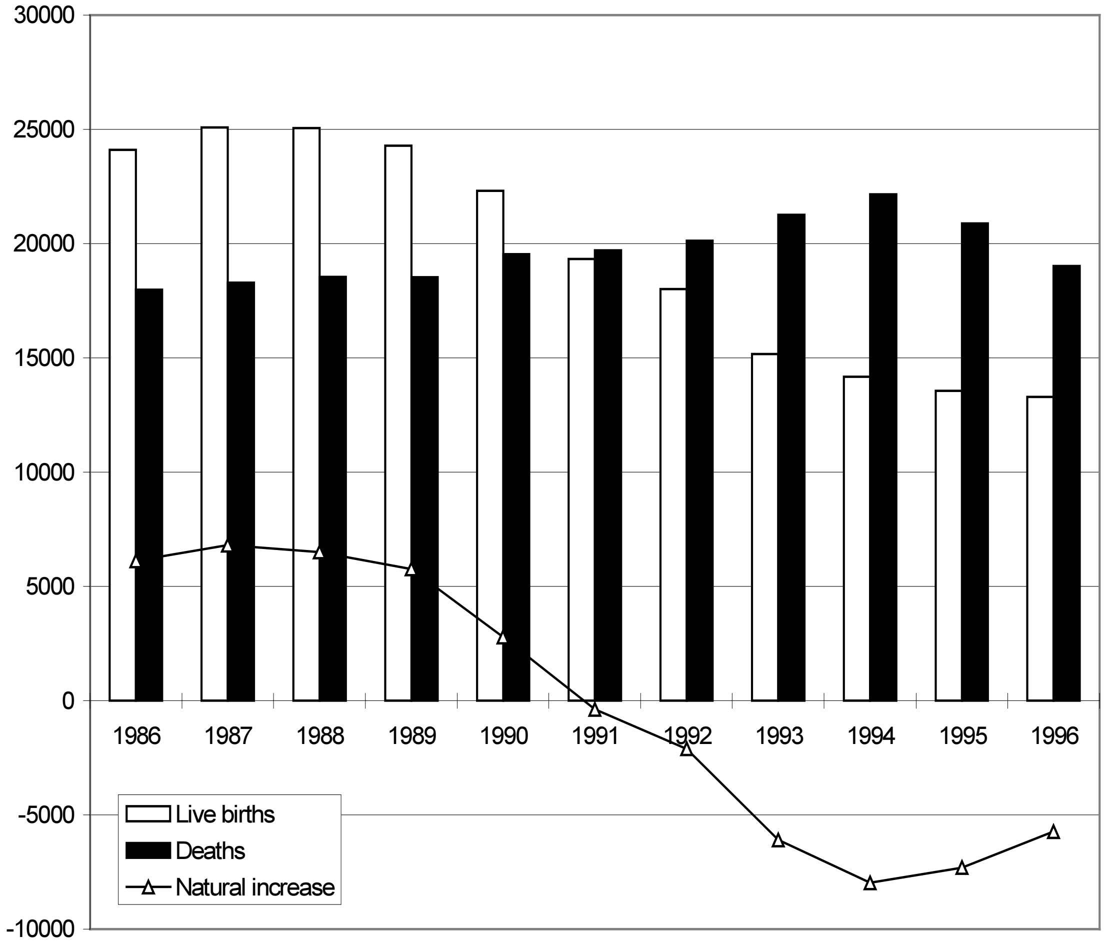
3 Human resources

The mean annual population number was estimated in 1995 as 1,483,942. Estonia's average population density is 32.8 persons per square kilometre, though there are approximately three square kilometres per capita. Five towns have over 50,000 inhabitants. The population density is above average in the three counties where Estonia's largest towns are located: Tartu (50.4 per sq. km), Ida-Viru (62.4 per sq. km) and Harju (130.9 per sq. km). The lowest population density is in Hiiumaa County (11.7 per sq. km). Rapid urbanisation started in Estonia in the 1960s. Today urban population accounts for two-thirds of the total, this proportion has stayed unchanged for the last decades.

The population of Estonia has been constantly decreasing in recent years due to two factors which have played an approximately equal role in the decline. First, the decline began in the early 1990s when the restoration of Estonia's independence resulted in a wave of departure of non-Estonian workers. Secondly, at the same time, the tendency towards the ageing of the population deepened due to the decreasing birth rate and a negative natural increase of the population (Figure 4).

The peak of emigration was in 1992 when the number of those leaving the country outstripped the number of new settlers by 33,700. In the following years emigration slowed down. However, the decrease trend of population deepened.

Figure 4 Births, deaths and natural increase (Statistical Yearbook …, 1996)

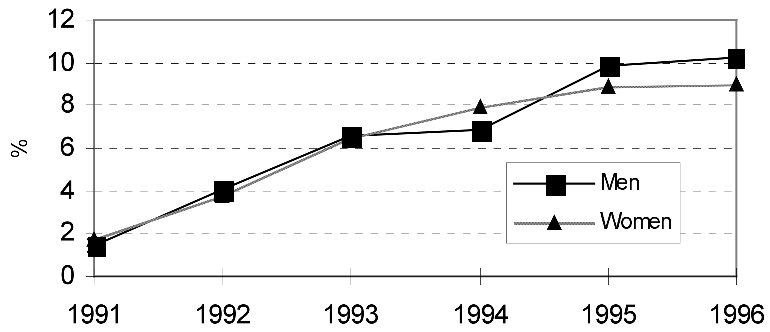


The unemployed were first registered in Estonia only in June 1991. From that time to the present, there are statistics on the receipt of unemployment benefits. In summer, unemployment goes down and rises again in the winter months. This can be explained by the increasing number of temporary positions in the summer (in agriculture, construction and services).

In Estonia, the unemployment rate is expressed as the ratio of the persons officially registered as unemployed to the number of people of working age.

There has not been any explosive growth in unemployment in Estonia. However, unemployment has been growing steadily. The rate of unemployed people reached 10% of the active labour force in 1996. The fastest growth of unemployment occurred in 1991–1993. While in 1991 there were only 2% of unemployed persons then by the end of 1993 their proportion was already 7%. Up to the year 1994 there was no difference in sexes. Since 1995 unemployment among men started to rise and in 1996 the unemployment rate was among men 11%, while among women it was 9% (Figure 5).

Figure 5 Development of unemployment in Estonia by sexes (Estonia's Second...,1998)



According to the ages the highest employment rate is among the young (15–24-year olds) – 16 per cent in 1996. Unemployment among the 25–49-olds varied from 9.8 in 1995 to 9.7 in 1996. The increase in unemployment among the 50–60 age group has been the slowest, reaching 6.5% in 1996. (Pettai, 1998)

Long-term unemployment is expected to remain at its relatively high level, as the period of receiving unemployment benefits will end for many people. The growth of long-term unemployment will become a serious problem in regions where unemployment during the last couple of years has been traditionally high: primarily in the south of the country and other regions farther away from county centres. Regional differences in unemployment are expected to grow due to the slow development of the rural areas and "overheating" of the economy of Tallinn and neighbouring regions. New regions with rapidly increasing unemployment rates may emerge.

In a long-term perspective, unemployment in rural districts will increase, possibly growing higher than in urban areas. The main reason for this estimation is the marked differences in the cost of living and the rate of economic growth in towns relative to the countryside. Being registered as unemployed is very important to people in many rural districts as it entails several important social benefits.

Hidden unemployment is expected to decrease, due to improved services by employment agencies and the expected rise in unemployment benefits that should motivate more people to turn to the agencies (Report on Estonian…, 1996)

4 Fiscal background

In 1997 the domestic savings increased to 5% against 3.5% in 1996, which then formed as a result of the difference between current revenue and expenditures in different economic sectors, at constant prices. In 1996 the domestic savings approximately equalled those of 1995, because the tight state budget considerably reduced the savings in the public sector.

The share of the salaries and wages fund in the GDP has been around 40%. In 1994 the share of wages and salaries in the GDP rose to 41.1% (38.7% in 1993). In 1995 it increased to 42.2% and dropped again in 1997 to 39.7%.

The great impact of foreign trade on state revenue poses no economic problem, but can cause some technical difficulties in predicting the development of the fiscal system. However, if in reality wages increase more than expected and foreign trade does not increase more rapidly than domestic trade, it will mean that the share of the state budget will decrease in the total revenue of the fiscal system. Since the share of income tax and VAT in the revenue of the fiscal system is high (nearly 75%), this will help to perpetuate the existing share of revenue in the GDP, provided tax rates remain unchanged. However, this can have a destabilising effect on the relations of the parts of the fiscal system.

Since the restoration of an independent state budget Estonia has pursued the policy of balancing revenue and expenditures. The foreign loans taken by the Government as well as domestic loans taken by local governments have been used for investments or renovations rather than for consumption. Disregarding state loans as well as loans guaranteed by the state and on-lent to production organisations, revenue and expenditures in the fiscal system were balanced in 1994–1995. In view of the increase in consumption and the decrease in savings in 1996 the Government set the target of achieving a budget surplus in both 1997 and 1998. The surplus will be channelled into the Stabilisation Reserve Fund, which will help the Government to finance unforeseeable expenses without having to increase the tax or debt burden.

The Estonian society seems to have come to a tacit agreement that taxes must not be too high. The tax level is usually measured as a ratio of tax revenue to the GDP. According to analysts, the wealthier the society, the higher the so-called normal tax burden. Wealth is measured by per capita GDP. Under this approach, Estonia's 35–40% tax burden is a bit too high for the country's level of development, but too low for affluent industrial countries such as Sweden or The Netherlands. Compared to other transition economies, Estonia can still be placed among the countries with a modest tax burden (that is, below 40% of the GDP). Estonia is exceptional in the sense that the relative reduction in the large amount of money being pumped through the budget system has not been followed by a spate of tax increases (at the end of the 1980s an estimated 43–44% of the GDP was redistributed through the budget system).

The Estonian tax system with its neutral character and overwhelmingly proportional tax rates should automatically guarantee a stable tax burden in the years ahead, provided that tax rates and the structure of GDP are not changed. The stability of the tax system is, of course, an important prerequisite for attracting foreign capital.

Foreign financing is dominated by long-term direct investments and loans. The investors are focused prevailingly on financing existing companies. The share of direct investments has been decreasing and reinvestments increasing. Highest investments have been made into industry and trade sectors. By the country of origin half of the investments have come from neighbouring Scandinavian countries, mostly Finland and Sweden, which have provided together over half of the investments.

Foreign loans taken and guaranteed by the state amounted in 1997 to US$ 310 million (based on average annual exchange rate in 1995 US$ 1 = EEK 11.46). Estonia's debt burden is relatively small as compared to other transition economies, approximately 5.6% of the GDP in 1997.

The inflation rate is slowing down gradually. During the last four years inflation has achieved a relatively stable and low rate compared to the previous years. Table 3 shows changes in consumer price index which relates closely to the change in inflation rate.

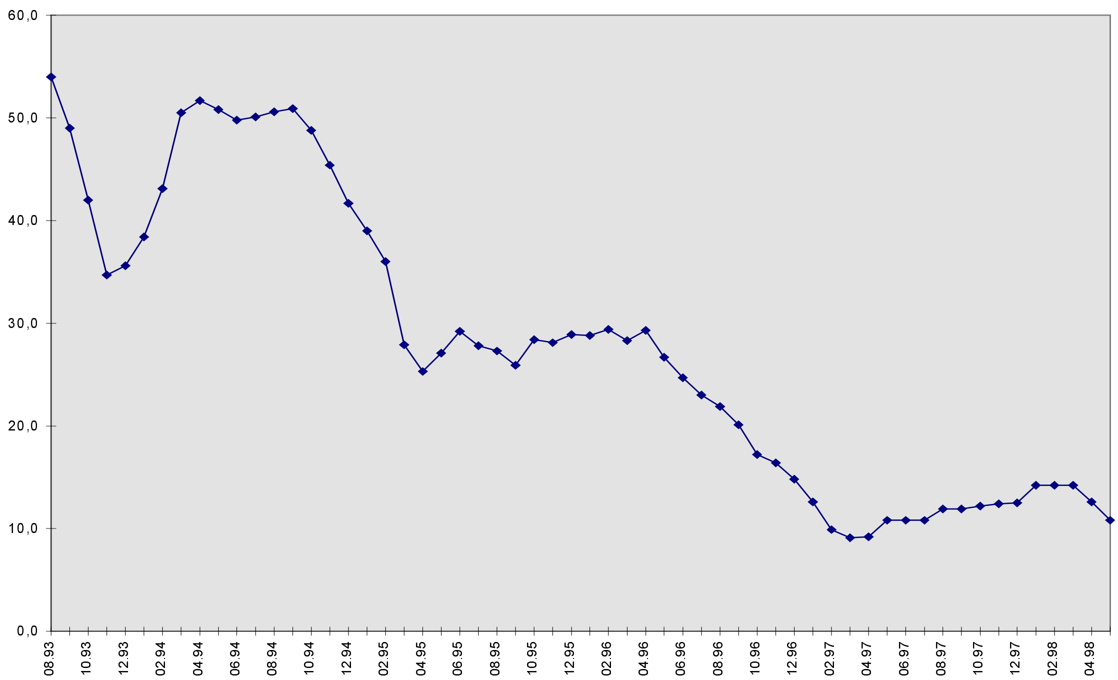
Table 3 Change in consumer price index compared to the previous year in %

	1990	1991	1992	1993	1994	1995	1996	1997
CPI	60	258.0	1053.0	89.8	41.7	28.9	14.8	11.2

The changes in the consumer price index (CPI) have been mostly caused by the fact that nearly all the prices are affected by the developments either on the domestic or world market. Domestic fluctuations are caused by price corrections in the sectors controlled by the State or local authorities or due to the interventions by the economic instruments in the form of taxes or other. Estonia as a small market is easily affected by any fluctuations in the world market. Actions taken by the trade partners are visible in the prices. All those factors are explicitly depicted in the case of the monthly increase in the CPI.

The dynamics of the CPI compared to the previous months is given in Figure 6. Here the trend of declining inflation rates is most explicit.

Figure 6 Changes in the consumer price index August 1993–May 1998 compared with the same month of the previous year, % (according to data of the Bank of Estonia)



Although the open sector has a significant impact on the price increase in the sheltered sector, this is not the only factor responsible for the price increase. The rapid increase in prices in the sheltered sector is closely related to administrative decision-making, that is state regulation of prices and the gradual freeing of prices from the state control.

The deregulation of prices began in Estonia already in 1988. The Government fixes the price of land, oil shale, standing forest, medicines, the rates of public health care services, communications and port services. Government ministries co-ordinate the prices of heating, gas, water and sewerage services. Local governments establish the fares in public transport and various communal services. The Competition Board monitors the prices of monopolistic companies.

Despite the short list of services with state-regulated prices their inflationary impact is relatively strong. There are several reasons for this. First, this is due to the fact that oil shale and electricity with their regulated prices are inputs that influence the country's entire economy. Secondly, the prices of the above goods and services have increased and will continue to increase in the near future at a higher rate than prices in other areas. Thirdly, goods and services with state-regulated prices make up approximately one fourth of the consumer basket used for calculating the CPI.

The future annual increase of the consumer price index is nevertheless expected to gradually fall in the medium-term perspective. For 1998 the predictions are a 9.6% increase, which will fall to 6% in 2001 (Ministry of Finance, 1998).

Estonia has a balanced budget. The major part of the budget revenue was formed from the value added tax (47.9%), personal income tax (16.6%), corporate income tax (8.8%) and income from excise taxes (17.1%) in 1997. The revenue from ownership and other (non-tax) sources increased gradually reaching 8.9% in 1997.

Expenditures of the public sector fluctuated from 38.3% of the GDP to 39.9% and back to 36.5% in 1997.

Since 1991, the basic means of balancing revenue and expenditures in drafting the budget has been proportional cuts of expenditures in all spheres. The period from 1991 to 1992 can be called the period of restoring Estonia's independent economy. After that, expenditures by category have been relatively stable.

Table 4 Budget revenue and expenditures in January–December 1996 (central government and local governments; million EEK) (Bank of Estonia, 1997)

	Central government budget	Local budgets	Total	
	million EEK	million EEK	%	million EEK
Corporate income tax	891.0		6.4	891.0
Personal income tax	4352.0		31.3	4352.0
VAT	5262.0		37.8	5262.0
Excise taxes	1731.0		12.4	1731.0
Other taxes and revenues	1004.0	664.3	12.0	1668.3
Total current revenue	13240.0	664.3	100.0	13904.3
Unused sums of previous period	180.0	151.8		331.8
Revenue (incl. Unused sums of previous period)	13420.0	816.1	102.4	14236.1
Transfers to local budgets	-3159.4	3159.4		
Revenue (incl. Transfers to local budgets)	10080.6	324.4		13904.3
Division of revenue between budgets, %	72.5	27.5	100.0	
Total expenditures	10046.0	364.2	104.0	10046.0
Division of expenditures between budgets, %	69.5	30.5	100.0	

The openness of the Estonian economy has facilitated the transfer of the Western price level and structure to Estonia.. One manifestation of this is the increase of import and export prices. The latter can first and foremost be attributed to the improved quality of Estonian goods, although it is impossible to measure the impact of this factor.

The price increase is also caused by the fact that at first Estonian exporters were little known and inexperienced to ask for the right price and thus goods were sold cheaper than those of the competitors. Export prices have also increased due to arbitrage, or selling goods priced low at home to buyers abroad at a higher export price. Due to the increasing real exchange rate of the kroon the possibilities of arbitrage are reducing.

Estonian trade has been in deficit for almost the whole economic transformation period. In 1996, 24.6 billion EEKs worth of merchandise was exported from Estonia while 38.4 billion EEKs worth of merchandise was imported. Thus, Estonia's trade deficit was 13.8 billion EEKs. In 1996 exports increased by 16.9%, imports by 31.8% and the trade deficit by 71%. In 1995, the trade deficit amounted to 38% of the exports, in 1996 it was 56%.

In total exports there are five groups of merchandise whose share has stayed between 11 and 17%: clothing, footwear and headgear; foodstuffs, machinery and equipment; timber and paper and products of the chemical industry. These groups have changed their positions over the last years.

In total imports, too, the five major groups of merchandise in 1996 were the same as in the previous year, and there was no change in their order. In case of the majority of groups of merchandise imports increased over 20%, and the import of metals, food and chemical products increased even over 40%. The only exception was mineral products.

5 Energy sector

5.1 Present situation of the Estonian energy sector

The post- World War II complex of oil shale power engineering was built to satisfy the energy demand of the north-western regions of the then Soviet Union, especially the Leningrad region. Immediately after the war, decision was taken by Soviet officials to restore and enlarge oil shale mining and processing. The target of the production was to supply Leningrad (currently St. Petersburg) with the gas produced from oil shale in retorting process in the town of Kohtla-Järve. The Kohtla-Järve–Leningrad gas pipeline was built and put into operation in 1948. Five years later, with further growth of oil shale gas production, the gas pipeline to Tallinn was opened in 1953. The electricity production on the basis of oil shale followed the gas generation. Oil shale power plants in Narva served those aspirations. After closing down gas production, the oil shale based chemical industry was developed. It was all created as a part of the all-Union production complex. Most investments into the production sector of that period were serving this interest.

During the period of Estonia's regained independence, the investments in oil shale based power engineering have been insufficient. By fixing the price on oil shale and electricity, the Estonian Government has proceeded from political considerations and from the solvency of customers. The production over-capacity exceeding the present market demand has mitigated the critical situation. The actually utilised production capacity is however lower than the data given in the statistics for 1996 due to the exhausted operational resources and replacements during repairs. The export potential of the winter peak capacity is almost exhausted.

Electricity production is fully monopolised in Estonia at present. Almost all electricity is produced by the joint-stock company Eesti Energia AS (Estonian Energy), whose all shares belong to the state. Practically all (99%) of electricity production is based on oil shale. The privatisation of the enterprise is underway at present.

Considerable changes have taken place in the energy sector during the last years. Both the primary energy demand (Table 4 and Figure 7) and the final consumption have decreased almost twice (Table 7). From 1993 onwards the level of energy consumption has gradually stabilised. In 1996 about 70% of the primary energy demand was covered by indigenous energy sources. The changes in the energy sector reflect reduction in the country's industrial output, but energy consumption has also become much more efficient during the last years (Long Term …, 1998).

Table 5 Estonian primary energy supply in 1990–1996 (StatisticalYearbook…, 1996)

Year	1990	1991	1992	1993	1994	1995	1996
Oil shale, %	58	56	66	63	63	63	63
Fuel oils, %	18	17	10	14	10	6	5
Motor fuels, %	12	12	10	13	12	13	11
Gas, %	13	13	11	7	9	11	12
Coal, %	2	2	2	1	1	0	0
Wood and peat, %	3	4	5	5	7	8	9
Electricity, %	-6	-4	-4	-3	-2	-1	0
Total supply, PJ	416.6	390.6	277.3	224.2	238.7	221.6	226.3
Share of domestic fuels, %	53	52	63	62	61	61	70

Figure 7 Primary energy balance by the types of fuels, PJ per year (Long Term …, 1998)

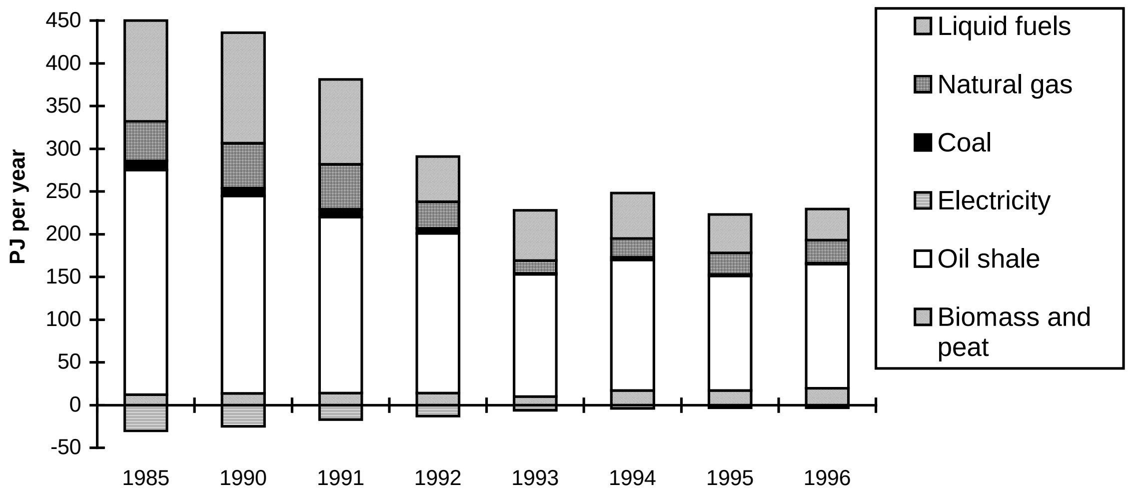


Table 6 Primary energy use in 1995, %

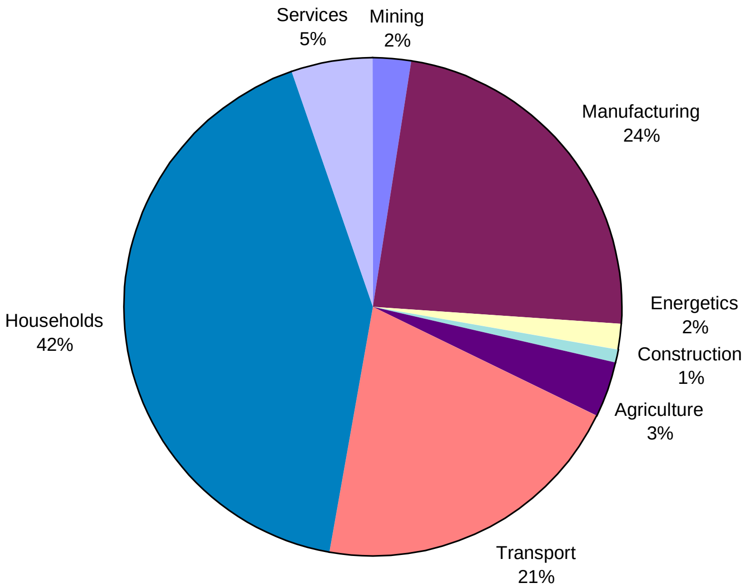
Category	Share in total supply, %
Electricity generation	43.0
District heat production	21.9
Oil shale processing	12.7
Peat processing	1.3
Direct use of fuels	17.7
Non-energy use	3.8
Fuel losses	0.7
Electricity export	-1.2

An overview of final energy consumption is presented in Figure 8 and Table 7.

Table 7 Final energy consumption 1990–1996, PJ (Energy Balance 1996, 1997)

Year	1990	1991	1992	1993	1994	1995	1996
Oil shale	6.0	5.7	4.5	2.1	3.4	3.1	2.9
Fuel oils	16.5	16.4	7.7	8.1	7.1	3.7	3.1
Motor fuels	49.6	46.8	26.6	28.3	29.0	26.3	25.6
Gas	9.5	9.8	5.8	4.2	4.9	4.6	3.9
Coal	5.9	6.1	2.2	0.8	0.3	0.3	0.8
Wood and peat	9.8	9.2	8.3	7.3	9.7	10.2	10.7
Electricity	26.3	25.9	21.3	17.4	18.6	17.8	19.0
Heat	89.9	89.0	60.5	45.9	42.0	40.3	42.2
Total, PJ	**213.4**	**208.9**	**136.9**	**114.0**	**114.9**	**106.3**	**108.2**

Figure 8 Estonian final energy consumption by economic sectors in 1995



5.2 Existing energy supply and demand system

Estonian industry has been quite energy intensive for decades. Economic recession, ongoing privatisation and restructuring have been the main reason for the significant diminishing of energy consumption. In connection with privatisation and according to changes in the energy supply and prices, an enhancement in improving energy use by the companies themselves is expected to rise. However, taking into account that most of the enterprises are in the midst of the restructuring process and that capital is very expensive, state is supporting energy efficiency measures in industry through assisting in carrying out energy audits and also in using soft loans. In households energy consumption has still has increased, but big fluctuations are taking place here.

Estonian energy supply system consists of electric thermal power plants and boiler houses. The production of electric energy is concentrated in Narva, Northeast Estonia, where the majority of electricity production capacities are installed. The installed capacity is actually higher than Estonian own demand. Plants were designed and built during the Soviet period to provide electricity for a much larger area in the north-western energy system of the former USSR – the Leningrad and Pskov oblasts of the

Russian Federation and Latvia (see Table 8). Oil shale power plants are old or close to being worn out. The estimated lifetime for Balti, Kohtla-Järve and Ahtme power plants is 10 years, for Eesti Power Plant 15 years and Iru Power Plant 25 years.

Beside the Balti Power Plant co-generation plants have been installed in Tallinn (Iru and Ülemiste) and in North-East Estonia (Kohtla-Järve, Ahtme). As for the electricity generation efficiencies, the net electrical efficiency of power plants ranges from 22% (Kohtla-Järve and Ahtme plants) to 27–29% (Balti and Eesti power plants), which could be considered relatively low.

Table 8 Larger power plants in Estonia (Statistical Yearbook…, 1996)

Plants	**Electricity capacity, MW**	**Heat capacity, MW**
Eesti PP	1610	84
Balti PP	1390	686
Iru CHP	190	749
Kohtla-Järve CHP	39	534
Ahtme CHP	20	338
Ülemiste CHP	11	278
Total	3260	2669
Share of Estonian total, % in 1995	100	20.8

Currently electricity production has dropped nearly by half, because export has diminished drastically (Table 9). This has a positive environmental effect enabling reduction of gross air pollution.

Table 9 Electric energy balance sheet in 1980–1995, GW·h (Statistical Yearbook…, 1997)

Item	**1980**	**1985**	**1990**	**1994**	**1995**	**1996**
Production	18898	17827	17181	9152	8693	9103
Imports	370	1379	1475	315	245	240
Consumption,	5500	6605	7299	5288	5075	5417
of which including industry	2992	3345	3450	2021	1943	2167
and household	514	734	881	1270	1067	1234
Own use by power plants	1735	1701	1733	1146	1086	1116
Losses (in networks and equipment)	960	1117	1147	1527	1773	1710
Exports (to Russia and Latvia)	11073	9783	8477	1506	1004	1100

The production of heat is based on a variety of fuels; liquid fuels have the biggest share followed by gaseous and solid fuels. Imported heavy and light fuel oils as well as locally produced shale oil are the major liquid fuels. In the majority of settlements district heating is used, the network of district heating is relatively well developed. In rural areas local boiler houses have been used, in many places heavy fuel oil fired boilers have been replaced with fuel wood based (wood chips) boilers. The share of local boiler houses is permanently increasing. Co-produced heat is consumed partially for district heating when feasible.

Significant changes have been taking place in heat consumption in various sectors, which is mostly due to economic restructuring of national economy. In industry and agriculture the decrease of consumption has been the biggest (see Figure 10).

Figure 9 Change of heat production capacities of power and heating plants

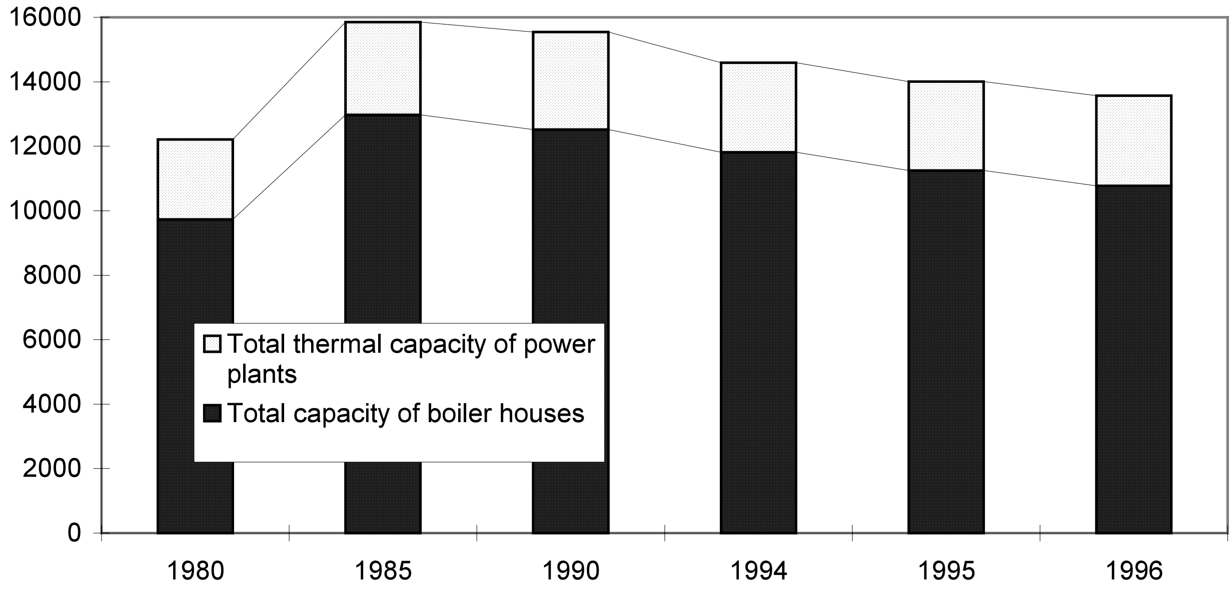
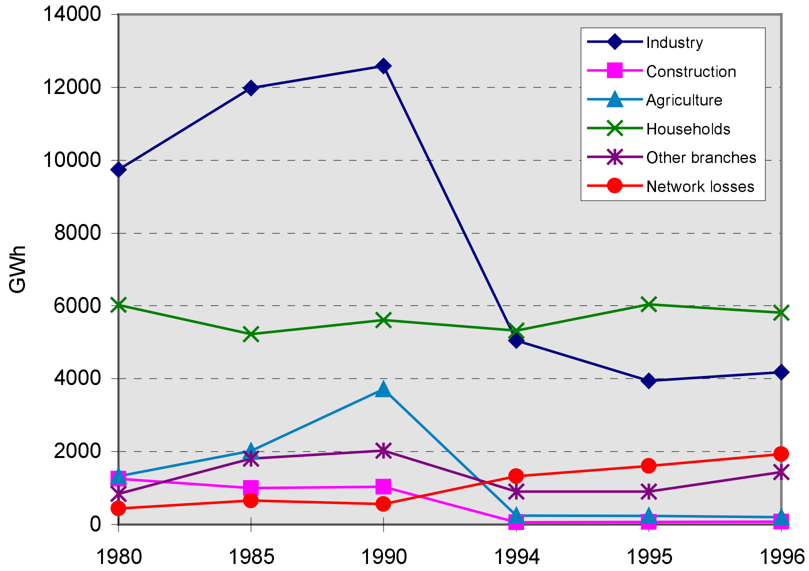


Table 10 Number of boilers, capacity and generated heat 1994–1996 (Statistical Yearbook…, 1996, 1997)

	Number of boilers at the end of year			Total capacity MW			Generated heat GW·h		
	1994	**1995**	**1996**	**1994**	**1995**	**1996**	**1994**	**1995**	**1996**
Total number of boilers	5586	5682	5267	11810	11252	10774	9206	9248	9561
Capacities: less than 1 MW	4271	4427	4051	2794	2591	2304	1746	1620	1521
1 to 5 MW	853	816	815	2231	2098	2003	1877	1559	1694
5 to 20 MW	392	374	340	3799	3570	3250	2597	2912	3074
20 to 60 MW	59	54	44	1802	1809	1570	1507	1499	1292
over 60 MW	11	11	17	1184	1184	1647	1480	1658	1980
Working with:									
Coal	1245	186	977	1133	725	555	383	325	285
Oil shale	133	100	86	198	205	200	135	151	164
Peat	184	172	121	254	301	439	223	319	410
Wood	769	908	885	902	1065	888	713	872	1032
Heavy fuel oil	912	723	676	4204	3178	2449	3620	2485	2561
Shale oil	711	692	513	1628	1593	1351	1234	1255	784
Light fuel oil	322	396	441	243	289	666	96	162	232
Gas	553	652	694	2785	3423	3722	2147	2985	3372
Electric energy	746	843	865	201	247	279	123	131	130
Other (generator gas and biogas)	11	10	9	262	226	225	532	563	591

Figure 10 Changes in heat consumption in different sectors between 1980 and 1996



The largest heat producer in Estonia is AS Tallinna Soojus, which has five large boiler houses in the city of Tallinn: Kesklinna, Ülemiste, Kadaka, Karjamaa, Mustamäe (capacities from 6 to 116 MW; production 1700 GW·h in 1995) and 45 smaller boiler houses with total production of 180 GW·h in 1995 in Tallinn municipality. The total length of the district heating network in Tallinn is 471 km.. The Iru CHP provided additionally 950 GW·h heat to the eastern part of Tallinn (Lasnamäe district).

About 80% of the consumers used district heating in the beginning of the 1990s. Of these 77% were households, 10% hospitals, schools and kindergartens, 8% shops and offices, 5% industry. However, those shares have been changing in recent years with the tendency to install small autonomous and efficient gas fired boilers in the buildings. Generally such small boilers give a better possibility to regulate heat consumption, hence to reduce the costs for heating.

The majority of district boiler houses in Estonia are depreciated. Only ca 1% of those are less than 5 years old, 15% are 5 to 15 years old, 44% 15 to 25 years old, and 40% are even older than 25 years (according to unofficial information from AS Tallinna Soojus). Of course there are differences in the age of equipment, some boiler houses have been renovated and boilers have been replaced, but a large part of boilers are truly old.

Efficiencies of the boiler houses are varying and are dependent on the age and types of fuels used. Boilers using solid fuels have the lowest efficiencies, 50–80%. The highest efficiency is for gas and light fuel oil fired plants – up to 85%.

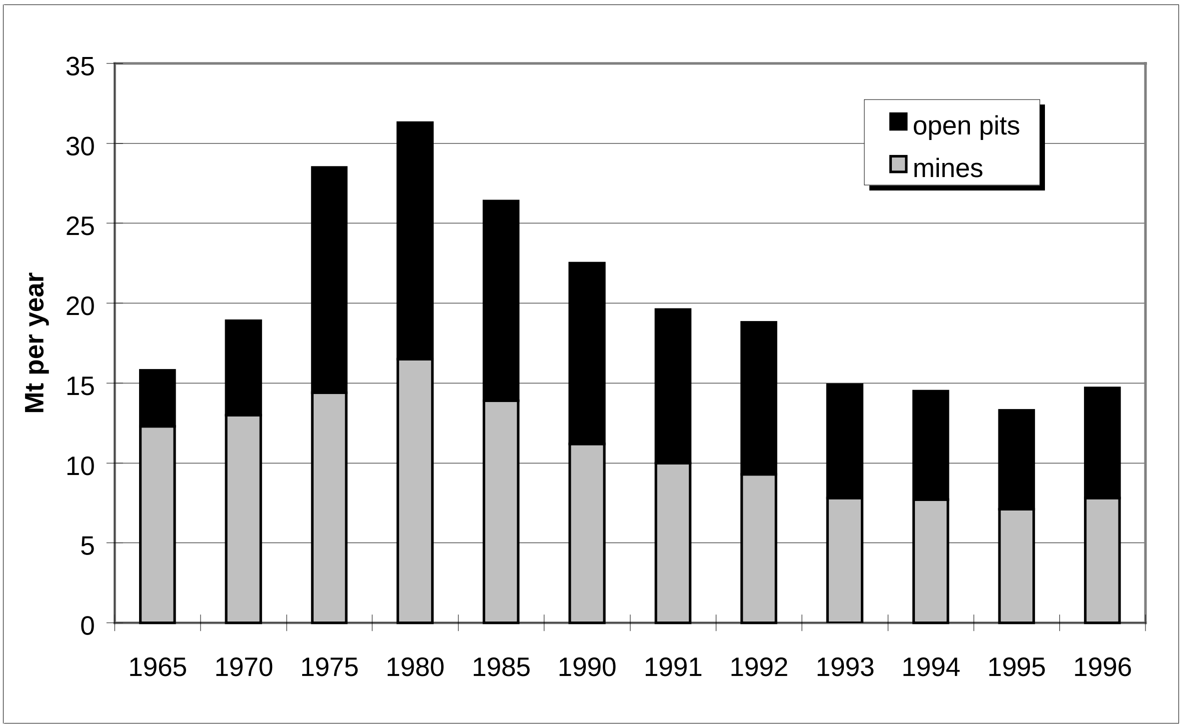
5.3 Energy resources

A specific feature of the Estonian energy sector is oil shale, which accounted for 63% of the primary energy supply in 1996. As much as 99% of electricity is generated from oil shale. Estonian oil shale is rather unique, its reserves are the largest commercially exploited deposit in the world. Oil shale is characterised as a low-grade fuel with a low heating value. Oil shale is a sedimentary formation which consists of organic matter or kerogen, carbonate matter and sandy-clay minerals (18–42%). Oil shale contains 1.2–1.7% sulphur, mostly as organic and pyritic.

Oil shale is mined in underground mines and open pits and the production capacities (see Figure 11) have changed in accordance with the demand of power plants and oil shale processing industry. The production cost of oil shale grows with the depth of the mined oil shale layers, decrease in its calorific value, increase in the cost of investments in transport and maintenance of the technical level, rise in the cost of blasting work and labour power and with the growth of environmental and resource charges (Long Term …, 1998).

Nowadays mining and quarrying occupy ca 8% of Estonian surface area. The annual extraction was 31.3 Mt in 1980, 22.5 Mt in 1990 and 13.3 Mt in 1995 (Figure 11). Every year some amount of oil shale has been imported also from Russia. Active resources of the Estonia's oil shale deposit are approximately 1.2-1.3 Gt and passive resources about 4 Gt.

Figure 11 Oil shale production in 1965–1996



Oil shale is used also for shale oil (synthetic crude oil) production and as a raw material for the chemical and cement industries. The oil shale consumption by purpose in 1995 was the following:

- electricity generation 72%,
- heat production 9%,
- shale oil production 16%,
- direct final use 2%,
- non-energy use 1%.

Oil shale is followed in the primary energy supply by natural gas with 12%, motor fuels with 9% and fuel oils with 5%. The share of peat and wood reaches 9%.

Consumption of natural gas has passed trough a significant drop during the big socio-economic reforms which have taken place since 1991 (Table 11). In general gas is considered to have a relatively low environmental impact. However, natural gas is a fossil fuel, whose combustion emits CO_2 to the atmosphere. The use of natural gas will probably increase in these regions where the use of biofuels and peat resources is not advisable. According to the development plan, the share of gaseous fuels in the energy balance has been foreseen to increase twofold, from the present 11% to up to 22% by the year 2010. The increased energy demand will mainly be covered with natural gas (Long Term …, 1998).

Table 11 Consumption of natural gas in Estonia (Statistical Yearbook…, 1997)

Year	1990	1991	1992	1993	1994	1995	1996
Consumption, Gm^3	1.516	1.524	0.888	0.442	0.644	0.723	0.799

To construct new gas pipelines international co-operation is needed in order to increase consumption. The security of supply of natural gas is of utmost importance as well. Up to the establishment of the unified gas network and for levelling gas consumption, a gas reserve will be stored in the Latvian underground gas storages and possible sites for Estonian own gas storages will be explored. The possible taxation of natural gas as a fossil fuel for the formation of the security reserve should be considered in the future, which would also promote the use of local energy resources, first of all wood and peat.

Peat could be considered a renewable energy source with some reservation in the frame of this work. However, some classifications still qualify peat as a fossil fuel. The total use of peat is comparable with the increase in peat reserves at present as about 22% of Estonia's area is covered with wetlands.

Main uses of fuel peat are heat generation (27% in 1995) and production of peat briquettes (50%). As the peat processing factories have their own backpressure turbines, a small amount of peat (2%) goes for electricity production. Peat briquettes are used for district heating (10% of 1995 production), domestic final use (51%) and export (39%). Total peat resources are evaluated to be 2.4 Gt.

Forests cover about 48% of Estonia's territory. Acceptable upper limit for annual cut is 7.8 Mm^3 of which the share of firewood could be 1.8–2.0 Mm^3. The growing stock gives 66–75% of wood and so-called logging residues (branches, stumps and bark) form 25–33%. About 35–40% of timber becomes the residue of wood industry. In addition to productive forest land, shrubberies on the former fields cover 200–300 thousand ha, where 1–1.5 Mm^3 of firewood could be supplied. Total forest harvesting in 1994 was 3.62 Mm^3, in 1995 the harvesting totalled 3.82 Mm^3, production of firewood was 1.52 Mm^3 and use of wood waste and wood chips totalled 0.4 Mm^3.

Real hydro potential is less than 1% of the present power generation capacity and there are no nuclear reactors. The wind potential is quite remarkable, especially on islands.

Oil, its products and coal are imported by rail and sea.

5.4 Security of supply

As the production of electricity is based on oil shale as a local fuel, then supplies of electricity can be considered as secure. Infrastructure for energy imports is quite well developed. Electricity networks are connected into a common network of the Baltic States and North-West Russia.

Problems with supplies may rise in connection with imports of primary fuels. Most easily affected sectors are therefore transport and heat production. At present Estonia is looking for energy carriers from more stable areas than Russia. This concerns mostly the supply of natural gas and heavy fuel oil.

The availability of alternative gas supplies would create favourable conditions for using gas turbines to produce electricity at peak hours, reduce the need for the construction or rehabilitation of polluting coal, oil shale or heavy oil fired boilers. The use of natural gas would be most sustainable in the context of environmental pollution. The total length of the high pressure pipelines is 900 km. Pipelines have connections from Russia and Latvia. Natural gas is supplied by the Russian firm Gazprom and delivered by the pipeline coming from south of Estonia.

Security of supplies is provided in a co-operation agreement between the Baltic States to use Latvian natural gas reservoirs as strategic reserves. Risks are diminished also by the fact that ownership of the Estonian gas company AS Eesti Gaas is divided between various investors. Along with Russian state-owned gas company Gazprom shares belong also to German Ruhrgas and the Estonian state. In order to seek independence from the single source, building gas pipelines connecting Estonia to the Nordic gas system is discussed.

Imports of oil and oil products are more diversified compared to gas. Oil products can be imported both by rail and by sea. The existing oil terminals at the Baltic Sea are capable to import and export crude oil and oil products. The largest terminals are in Tallinn – Tallinn and Muuga. Smaller ones are located along the coasts of islands (Roomassaare in Saaremaa and Lehtma in Hiiumaa) and the northern coast of the mainland (Paldiski and Sillamäe) and these are able to supply those regions. Total planned capacities are over 25 million tonnes of oil and oil products per year. However, achieving these capacities is questionable because of tough competition between oil terminals. Building an oil pipeline from the closest oil refinery Kirishi in the Leningrad oblast (Russia) to the Estonian Muuga oil terminal has been under discussion. Also, building an oil refinery has been discussed. As to pipeline construction, there is a competitor – Porvoo refinery in Finland – and it is most likely that a pipeline will be built to Finland instead. Estonia is a re-export country for oil products.

Coal is imported by rail as well as by sea. The major importers are Russia and Poland.

5.5 Costs of local energy resources and imported fuels

The costs for imported fuels have undergone drastic changes since Soviet time. Previously highly subsidised fuels made it beneficial to import fuels only from the constituent republics of the Soviet Union or countries of the socialist bloc. Subsidies for imported fuels were abolished in the beginning of the 1990s and fuel prices in Estonia are the same as on the world market and they are dependent on fluctuations on those markets. This applies also to imports from Russia.

Table 12 Comparative consumer energy prices including taxes in Estonia in 1995 (The Ministry of Economic Affairs, 1996)

Type of fuel	Price in EEK/MW·h	Price in US$/MW·h
Electricity	390	33.1
Natural gas	185	15.7
Heavy fuel oil	81 ... 144	6.9 … 12.2
Coal	62 ... 111	5.3 … 12.2
Peat briquette	60 ... 99	5.3 … 9.4
Wood waste	38 ... 89	5.1 … 8.4
Peat	37 ... 62	3.2 … 7.5
Firewood	36 ... 79	3.1 … 5.3
Oil shale	34	2.9

The actual fuel prices on the Estonian market include also the excise tax (Table 12). Fuels for district heating plants were exempt from value added tax (VAT). This is important to note when making comparisons.

The prices on energy and fuels have been increasing rapidly in Estonia. The prices on liquid fuels, natural gas and coal have grown by leaps to the level of the European free market prices and only the share of taxes in the price structure differs from that in the sales prices of the countries with market economy. The prices on indigenous fuels (oil shale, peat and wood) have constantly grown, but remain still significantly below those of solid fuels (per calorific value unit) in our neighbouring countries. The average price on oil shale based electricity has reached the level of inexpensive Norwegian hydropower based electricity, but remains still significantly below the price level of other European countries, including the relatively low prices of electricity in Finland and Sweden. In 1997, the price of electricity for household consumers was 0.60 EEK/kW·h in Estonia while it was 2.59 in Denmark, 1.60 in Finland, 1.82 in Sweden and 0.71 EEK/kW·h in Norway.. Thereby the share of taxes in the price for household customers made 61% in Denmark, 58% in Sweden, 27% in Norway (all the prices are based on the exchange rate for 12 August 1997) and 15.3% in Estonia (Long Term…, 1998).

In accordance with the decision of the Riigikogu from 1997, electricity generated on the basis of renewable resources is not taxed with VAT.

6 Energy policy

6.1 Energy sector priority issue

The Government of Estonia has identified the development of the energy sector as a strategic component in the stable development towards a market economy. As a factor of production, energy contributes to the overall development of Estonia. Estonia has substantial domestic primary fuel resources of oil shale, peat and wood, also waste products from forest as well as secondary fuel resources of shale oil. At the same time Estonia lacks natural gas, oil and coal, those fuels have to be purchased at world market price level.

Energy prices have been increasing continuously since 1990 and energy costs form a significant share of the expenses of households, industry, public buildings, etc. They are a burden for the structural adjustment of the national economy and balance of trade. Changes in energy prices towards the world market price level of natural gas, coal and petroleum products and to the level that will cover the costs of production of oil shale, electricity, shale oil and district heating have significantly influenced consumption. It is most evident in the production process and in the households' budget for heating and electricity. Increasing prices of energy carriers lead to falling real disposable income.

The main goal of Estonia's energy policy is to encourage energy efficiency in the production, distribution and transmission processes and also at the end user. Increased energy efficiency will also contribute to the improvement of the environmental situation in the oil shale region in the north-east of Estonia. High energy prices alone would not be a sufficient condition for any progress in the energy sector. Market alone will not be able to ensure an increase in efficiency and solve the related environmental problems. Therefore the role of Governmental policy in the energy sector is of extreme importance.

The priority issues of the energy sector, on which policies should be aimed for further improvement, can be listed as follows:

- low efficiency of energy facilities and buildings, lack of sufficient contemporary know-how;
- requirements for governmental subsidies for the household sector and cross-subsidies;
- dependence on fuel imports, primarily gas, coal, oil and petroleum products;
- negligence of environmental protection measures, primarily in the oil shale production sector;
- shortage of financial resources for investments in the energy sector. Limited access to foreign financial resources and at the same time insufficient capabilities in investment preparation and implementation;
- inadequate legislative and institutional framework.

6.2 Energy policies prospective

The main goal of the Estonian energy policy and strategy is to improve the efficiency of production, transmission, distribution and consumption of energy. To achieve it the main guidelines to be followed in the near future can be figured out:

1. **Ensuring a stable domestic and imported fuel supply**. Oil shale, peat and wood are produced in Estonia, the rest of the fuels have to be imported. Policies are aiming at creating alternatives in the supply of natural gas, light and heavy fuel oil and gasoline from the countries around the Baltic Sea other than Russia. Estonia, as well as the other Baltic States, is interested in possibilities to import natural gas from the North Sea. International co-operation should be developed to achieve this.
2. **Improvement of the efficiency and reliability of existing supply systems** through rehabilitation and investments into new technologies in power plants.
3. **Decrease in capital expenses**, which are very high at present. The relatively high market interest rate may turn it unrealistic to invest into energy efficiency. Government has an assignment to decrease the interest rates and to decrease the capital expenses by this way.
4. **Further intensive development of Estonian oil terminals** for the transit of liquid fuels. Estonia could serve as the main mediator for Russian oil export to the West.
5. **Improvement of the diversity of energy supplies** through utilisation of domestic resources. Increase in the share of local fuels in heat generation in the municipal sector, particularly in smaller towns and villages. Also renewable energy, in particular wood in the form of wood chips has a certain niche. This allows reduction of the dependence on imported fuels and a decrease in local unemployment. Zero emissions of carbon and sulphur have an outstanding role to play. It is of high importance particularly in rural areas. Policies are oriented towards subsidising the consumption of local fuels by giving favourable loans either for fuel production or stimulating the consumption itself, e.g. reconstruction of boiler houses.
6. **Enhancement of the efficiency of energy production and consumption** through cost effective measures. The enhancing comprises the implementation of the Energy Conservation Programme and supporting all the activities

connected with it. It is considered of high importance to create alternatives in energy production and stimulate the widening of market.

7. **Improvement of the efficiency of resource use and decrease of pollution** by further development of the taxation system. Technology transfer is the key issue to introduce cleaner technologies in heat and electricity production. Relatively big investments are needed to solve the environmental issues at contemporary level.
8. **Elaboration of the legislation** on energy production and consumption. Introduction of regulations is necessary in order to protect customers by ensuring fairness of pricing.
9. **Promotion of co-operation** with other countries, particularly with Latvia and Lithuania.
10. **Attraction of foreign capital** for rehabilitation of energy systems and facilities.

Considering the most probable energy policy option, Estonia will rely on local fossil fuel, oil shale, in the future. Therefore it is vital to develop new oil shale combustion technologies, based on modern techniques of combustion. Studies on new combustion technologies like fluidised bed etc. have been conducted by various institutions.

The Energy Sector policy is based on various energy development plans: the Energy Development Plan to 1995; Energy Development Scenario to 2030; Energy Master Plan for Estonia; Energy Programme "Energy 2000"; Refurbishment of the Narva Power Plants and the Optimisation of Oil Shale Mining in Estonia; National Energy Strategy; Long Term Development Plan for the Estonian Fuel and Energy Sector.

The main strategic objectives of the energy sector based on the above-mentioned documents have been set as follows:

- to provide a sufficient and stable fuel and energy supply in conformity with the required quality and with optimal prices for consistent regional development and for reaching the economic growth required for the accession to the European Union;
- to provide the political and economic independence of the state by the fuel and energy supply as a strategic branch of economy; to establish the strategic security reserves in conformity with the requirements of the European Union;
- to establish legal basis for regulating Estonian power engineering;
- to promote the use of local fuels through price regulation and tax policy;
- to implement the programme of the oil shale mining and power production on the basis of oil shale;
- to provide higher efficiency in oil shale based energy production with the concurrent and significant reduction of the harmful environmental impact via the renovation of combustion technology;
- to provide conformity with the international environmental regulations, particularly with those of the European Union;
- to develop the standards, implement international agreements, and guarantee the implementation of the directives of the EU;
- to increase the possibilities of importing liquid fuels;
- to establish an actually working energy conservation system for the fuel and energy production and use;

- to prefer the principle of scattered electricity production and combined heat and power production by planning new power plants with the concurrent optimal use of the available heating capacities;
- to identify and solve the strategic and technical issues of supply, distribution and use of gas in the Baltic states;
- to promote wider use of renewables with applying tax allowances both on the respective investments and energy production based on those investments;
- to apply administrative measures in the introduction of different ownership forms, guarantee the rights of the property owners;
- to improve the security of energy supply by international agreements (for the maintenance of energy facilities on the border with the Russian Federation, fuel and energy supply agreements with neighbouring countries for the storage of emergency and security reserves).

Privatisation is one of the key areas which has its strong influence on the current and future energy policies. Heat production plants are already largely municipality owned. State owned electricity transmission networks are being reorganised also. Preparation of power plants privatisation is in progress. AS Eesti Energia (Estonian Energy) and AS Eesti Põlevkivi (Estonian Oil Shale) are among the companies to be privatised in 1998 (The Privatisation Program…, 1997).

To motivate the use of domestic renewable fuels, wind and hydro energy resources for power and heat generation, a proposal of laws and regulations that envisages the minimal selling price of electricity generated on the basis of these fuels to the public grid, was given to Riigikogu. In June 1998 Riigikogu decided to amend the Estonian Energy Act, which involves obligation to buy wind generated electricity by public grid at preferred price level.

7 Climate Change Issues

Estonia signed the UN Framework Convention on Climate Change (FCCC) during UNCED in Rio de Janeiro in 1992. In May 1994, Riigikogu approved the ratification of the Convention and the President promulgated the Act on Ratification. In July 1994 Estonia deposited its instrument of ratification and the Convention entered into force for Estonia in October 1994. A governmental committee on the implementation of the Convention was created in January 1995. The committee's tasks are to consider questions such as greenhouse gas emission reductions strategies and activities implemented jointly.

Estonia presented its first national communication under Articles 4 and 12 of the Convention to the COP in March 1995. Several ministries and institutions contributed to this report. Estonia was assisted in the preparation of its communication by the United States in the framework programme "US Support for Country Studies to Address Climate Change". The second national communication under the FCCC has been presented to the Secretariat in spring 1998. According to it the total emission of GHG decreased significantly to the year 1996 compared with 1990 (Table 13). As for CO_2 the decrease has been almost twofold.

The largest GHG emissions in the energy sector are caused by energy conversion processes while burning fossil fuels. Oil shale burning is the major source followed by liquid fossil fuels, a much smaller share belongs to natural gas, coal, peat and coke (see Table 13).

Table 13 CO2 from energy sources, Gg (Estonia`s Second…, 1998)

Fuel Types	1990	1991	1992	1993	1994	1995	1996
Fossil fuels total *	37183.8	36342.2	27453.3	21786.0	22667.5	20637.6	21216.2
Liquid fossil fuels	9734.4	8566.6	5023.4	5191.38	4782.3	3721.6	3647.2
Natural gas liquids	95.6	91.9	40.4	21.6	30.3	21.2	14.2
Gasoline	1688.4	1417.3	681.4	694.6	858.1	649.6	740.8
Kerosene	335.7	262.7	68.8	157.6	147.2	70.4	139.3
Jet kerosene	112.1	109.9	37.3	57.4	47.4	52.5	49.0
Diesel oil	1887.0	1826.2	1198.9	1280.1	1174.7	1100.0	1043.4
Heavy fuel oil	5500.2	4700.0	2921.2	3229.2	1975.0	1247.5	1194.4
Other oil	115.4	158.6	75.4	525.3	549.6	580.5	466.1
Solid fossil fuels	24595.4	24908.6	20753.5	15761.6	16690.2	15549.9	16064.7
Oil shale	23051.4	23011.7	19347.8	14854.9	15867.1	14727.1	15196.7
Coal	880.1	863.4	536.3	282.4	211.6	201.1	229.2
Peat and peat briquette	653.7	1024.1	861.3	615.9	605.3	615.6	635.6
Coke	10.2	9.4	8.1	8.4	6.3	6.2	3.1
Gaseous fossil	2854.0	2867.0	1676.4	833.1	1193.8	1366.1	1504.4
Natural gas	2854.0	2867.0	1676.4	833.1	1194.9	1366.1	1504.4
Biomass total	1074.0	796.5	843.7	793.4	1289.3	1445.9	1613.5
Solid biomass	1074.0	796.5	843.7	793.4	1289.3	1445.9	1613.5

* biomass is not included into fossil fuels total

Distribution of GHG emissions between different sources and dynamics during the 1990s in Estonia is depicted in Table 14.

Table 14 Changes in GHG emissions in Estonia, Gg (Estonia`s Second…, 1998)

Source and Sink Categories	1990	1991	1992	1993	1994	1995	1996
Carbon dioxide	36251	35189	25136	19597	21527	17363	18549
Energy and transformation	34528	33957	26030	20179	20882	18938	19682
Transport	2656	2386	1423	1607	1786	1700	1534
Industrial processes	613	614	313	193	215	222	206
Land-use change and forestry	-1545	-1767	-2630	-2382	-1355	-3496	-2874
Methane	105.2	102.1	91.3	79.7	79.5	67.7	63.2
Fuel combustion	2.6	2.5	1.9	1.6	1.8	1.7	1.8
Agriculture	60.2	60	54.7	47	46.4	34.3	30.2
Waste management	42.4	38.6	34.7	31.1	31.3	31.7	31.2
Nitrous oxide (N_2O)	2.3	2.3	1.7	1.4	1.3	1.2	1.2
Fuel combustion	1.4	1.4	1	0.9	0.8	0.8	0.8
Agriculture	0.9	0.9	0.7	0.5	0.5	0.4	0.4

The big decrease in GHG emissions during a relatively short time occurred mostly due to the huge restructuring of the whole economic system explained in detail above.

Estonia's platform to Kyoto UN FCCC Conference of Parties was in conformity with the European Union's one: 10% reduction of CO_2 to the year 2005 and 15% to 2010. In general, this shows a high commitment of Estonia to further reductions of GHG emission.

8 Concluding remarks

Estonia is one of the countries in transition where political changes caused accelerated socio-economic development of the country in the beginning of the 1990s. The drastic drop in energy consumption in some key sectors like industry and agriculture in the period 1990–1996 is characteristic indicator showing considerable restructuring of former important sectors in the national economy. From the point of view of impact of global climate change on different sectors, agriculture and forestry could be considered the most vulnerable to climate change. Long term climate change would affect those particular sectors most of all. As the changes in socio-economic development have been considerable during the transition period from a centrally planned to a market economy, climate change impacts should be carefully studied and differentiated from those caused by social and economic changes in the whole state. The same problem is characteristic for most countries in transition. Big changes and restructuring of the whole socio-economic development actually tend to overshadow the global climate change impact.

As the oil shale based power generation is the biggest GHG source in Estonia, the ways to reduce the total emission are of high priority in implementing the obligations of the UN Framework Convention of Climate Change. About 99% of electricity generation and about 15% of district heat production is based on oil shale combustion. In spite of an almost double decrease in energy production since the beginning of the 1990s, the energy sector remains the biggest source of GHG emission at present, therefore the main concerns are connected with it. As oil shale is a low-grade fossil fuel, electricity generation with presently used pulverised combustion technology gives significant emissions of CO_2, SO_2 and alkaline fly ash into the atmosphere. CO_2 is critical from the aspect of climate change, the rest of pollutants, particularly SO_2 have been creating big environmental threats to the north-eastern part of the country and the neighbouring republic of Finland during many decades. According to a bilateral agreement with Finland on reduction of sulphur emissions, Estonia has to decrease the emissions of SO_2 by 80% to the year 2005 compared with 1980.

Principally new technologies of oil shale based heat and power generation have gained popularity as an urgent need exists to phase out inefficient, highly polluting and worn out technologies of energy production. New methods of oil shale burning like Pressurised Fluidised Bed Combustion technologies facilitate significant reduction of the decomposition rate of carbonates in the mineral part of oil shale as well as the content of CO_2 in flue gases. Using the new technologies of oil shale combustion the emissions of sulphur compounds will almost disappear.

The liberalisation of energy market will create a new situation in Estonia. The present monopoly in the power generation has shifted the normal functioning of the market, therefore lifting constraints will probably bring about many new opportunities. Also carbon taxation has a considerable role to play. According to the results of analysis of the present study, the old technologies of using oil shale will be phased out, the use of natural gas will increase, wind energy may gain much bigger role, the use of wood as a fuel will rise and even high cost energy conservation measures will become realistic. However, the practical decision-making in designing the future energy policy will depend on many issues like the forthcoming privatisation of the power sector, security of supply of imported fuels, further development of the concept of the Baltic Energy Ring, social and political aspects connected to possible changes in the oil shale mining industry, etc.

Renewable energy, being rapidly developed in many European countries like Denmark, Germany, the United Kingdom, etc. has brought about a certain enlivening also in Estonia. Estonia is actually rich in such renewable energy resources like wood, peat and wind. Wider use of renewable energy sources would allow significant cutting of GHG emissions. From year to year, the wood has been more widely used for district heating. Wood supply for the production of wood chips for boiler houses is reliable and stable and it creates new jobs in rural areas. The use of wood in heat and power generation means net zero emissions of carbon to the atmosphere. Also, compared to heavy fuel oils, significant reduction of other pollutants, particularly sulphur, will take place. From the viewpoint of the impact on climate, wood is preferred to various fossil fuels like coal, oil shale and natural gas. Its big advantage is also the positive influence on reducing social and economic problems.

Wind energy potential is rather good in Estonia due to its geographical location. This potential could be efficiently used particularly on the western coastline and islands. On the basis of expert assessment the practically achievable annual production generated by wind turbines could be up to 0.3 TW·h electricity. However, wind could never be defined as an energy source able to cover total demand. The most probable would be a step-wise start with wind turbines on small islands with no public grid available at present. Diesel generators combined with wind turbines might be the option for electricity generation.

According to the Long Term Development Plan for the Estonian Fuel and Energy Sector, which was adopted in the Riigikogu in February 1998, the role of renewable energy sources in the primary energy supply has to increase from present 8% to 13% to the year 2010. Strong support from the Government has a significant role to play here. In a number of cases technology transfer projects need long term loan guarantees from the state.

An important goal of Estonia's energy policy is to further encourage the efficiency in the production, transmission and consumption of energy. Both the supply and demand side efficiency rises are of high priority and have a big potential (up to 30%) to reduce the emission of CO_2. Cutting of huge losses in transmission networks is of high importance at present. Also energy conservation issues started to be highly prioritised in Estonia. The whole economic system should be oriented to market and liberalisation of prices, which together with well-planned governmental energy saving policy could give economically founded GHG mitigation options.

An analysis of the existing combustion technologies

1 Review of the existing combustion technologies

It is quite possible that Estonia will continue to use oil shale as a fuel in the future. This could contribute to the security of supply and will maintain independence from imported energy resources. Intensive use of oil shale for energy production in the future requires considerable improvements of existing power plants. Therefore Eesti Energia has planned several activities. Among the main aims established are the following: to increase the efficiency of power plants, to reduce the level of SO_2 emissions, to improve ash removal. To achieve these aims Eesti Energia with co-operation of Tallinn Technical University has conducted research into the use of circulating fluidised bed (CFB) and pressurised (PFB) combustion technologies for oil shale instead of the pulverised combustion (PC) technology. These combustion technologies enable to increase the SO_2 capture efficiency and facilitate a substantial reduction of the decomposition rate of carbonates in the mineral part of oil shale, and that of CO_2 content in flue gases of oil shale power plants. Several other cheaper SO_2 removal methods (wet gypsum process, semi-dry process, Ahlström scrubber) are being tested and studied for flue gas cleaning if PC technology is used (Refurbishment of the Narva..., 1995).

1.1 Pulverised combustion of solid fuels

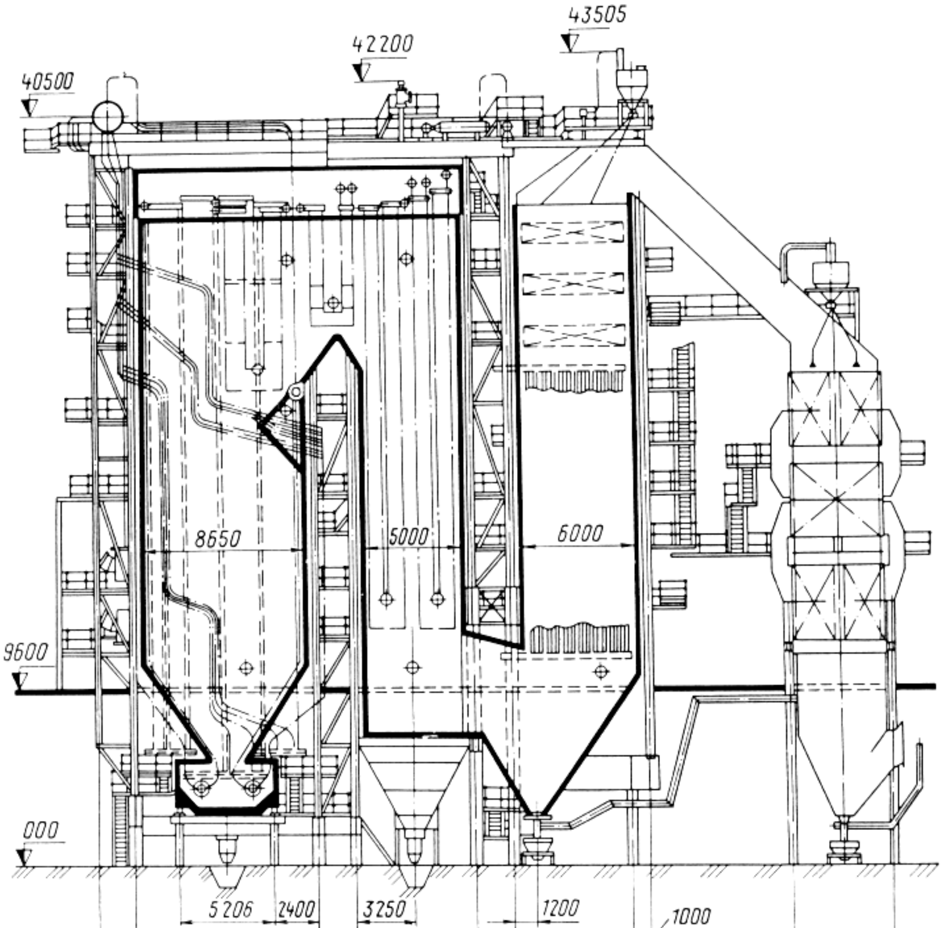
Pulverised combustion of solid fuels is mainly used in thermal power plants all over the world. Significant research and development efforts are directed toward improving characteristics of conventional pulverised solid fuels fired power plants. The average efficiency of conventional pulverised coal fired power plants is about 33% and that of advanced pulverised coal fired power plants is about 38% (Sathaye and Meyers, 1995). In Estonia 98.5% of the total electricity consumed is produced on the basis of pulverised oil shale.

The efficiency of the Estonian Power Plant is 29% and that of the Baltic Power Plant is 27%. The efficiencies of the Kohtla-Järve and the Ahtme CHP Plants are about 22%. The low efficiency of oil shale fired power plants can be explained by the peculiarities of burned oil shale.

Pulverised combustion of oil shale with a high ash content in power plants poses specific problems, such as: the behaviour of inorganic matter in the combustion process, fouling, high temperature corrosion and wear of the steam boiler's heating surfaces. First of all, one should mention the tendency of free lime-rich oil shale ash (the free CaO content in different ash fractions is 6 to 20%) to a severe fouling of heating surfaces with sulphate-bound fly-ash deposits. Being caused by the potassium components (mainly KCl) formed in the combustion process, the corrosion of the steam boiler's heating surfaces is also considerable. The frequent cleaning of the latter from fly ash deposits leads to a very severe corrosive wear of boiler tubes. The above-mentioned circumstances were the reason why the normal work of the boilers designed to be fired with coal or brown coal was impossible in case of burning oil shale. Therefore, special pulverised oil shale-fired boilers TP-17, TP-67 and TP-101 were designed for operation in big power plants. TP-17 was designed for 100 MW and the other two for 200 MW power generating units (double units). All these steam boilers are characterised by the lack of thick tube packets and a wide use of screen and single-pass panel heating surfaces, as well as the relatively low gas velocities to reduce fouling, while all the heat transfer surfaces have been equipped with special cleaning devices. To diminish corrosion the temperature of the overheated steam has been lowered to 500–520°C.

Despite all that, the operation of pulverised oil shale fired boilers takes place in heavy-duty conditions and great expenses are required to clean and repair the boilers. The advantage of oil shale fired boilers is the fact that due to a high volatile content of the organic part of oil shale they can operate also at very low loads (up to 40%). A schematic diagram of the TP-101 boiler in operation at the Estonian Power Plant is shown in Figure 12.

Figure 12 Schematic diagram of the TP-101 boiler of the Estonian Power Plant



1.1.1 Flue gas desulphurisation

The statement between Estonia and Finland, signed in 1993 (Refurbishment of the Narva..., 1995), set the following targets:

- 50% reduction in SO_2 emissions by the end of 1997 from the 1980 emission level and
- 80% reduction in SO_2 emissions by the year 2005 (only recommendation) from the 1980 emission level.

All the reductions necessary for the whole Eesti Energia Ltd. are directed to the Estonian and Baltic Power Plants, because the SO_2 emissions from these power plants form approximately 70–80% of SO_2 emissions of the whole country.

Table 15 gives specific SO_2 emissions comparing them to typical emission factors of some other fuel and to the emission limits in the European Union (Refurbishment of the Narva..., 1995).

Table 15 Specific SO_2 emissions, MSG/MJ

Narva plants	1980	1988	1992	New plant EU[1] limit value	Coal [2] (1.0%S)	Heavy fuel oil (2.5%S)
Baltic PP						
Boilers TP-17	1360	1125	1360			
Boilers TP-67	1000	900	880	200	700	1200
Estonian PP						
Boilers TP-101	734	660	820	200	700	1200

[1] SO_2 emission limit value for solid fuel fired power plant with a capacity of 500 MW_{th} or more (capacity scale of BPP and EPP)

[2] Typical emission without any sulphur capture

Examination of Table 15 leads to an observation that average specific SO_2 emissions from the Baltic and Estonian Power Plants are fairly high, varying from 660 to 1360 mg SO_2/MJ. This is the situation in spite of remarkable sulphur capture (70–80%) by other fuel constituents of oil shale.

Table 16 SO_2 required reductions from 1980 level, t SO_2/year

SO_2 reduction	2000	2005
Base case 1 includes domestic demand + 1 TW·h electricity export + 0.2 TW·h grid losses		
50% reduction	14000	26000
80% reduction	77000	88000
Case 2 includes only domestic demand		
50% reduction	2000	14000
80% reduction	65000	76000
Case 3 includes domestic demand + 3 TW·h electricity export + 0.5 TW·h grid losses		
50% reduction	40000	59000
80% reduction	103000	121000

SO_2 emission reductions required at the Narva power plants in order to achieve the emission target levels laid out in the Estonia–Finland statement for all the sources of SE Eesti Energia are given in Table 16 (Refurbishment of the Narva..., 1995).

1.1.2 CO_2 emissions

Energy-related activities are the most significant contributor to Estonia's greenhouse gases (GHG) emissions. In 1994 the share of CO_2 emission from oil shale burning formed 75% from all energy-related activities. The total CO_2 emissions from oil shale burning were 16,350.8 Gg (Hamburg et al., 1996). From the point view of GHG emissions it is important that during combustion of pulverised oil shale CO_2 forms not only as a burning product of organic carbon, but also as a decomposition product of the carbonate part of ash. The formula for calculating the carbon emission factor for fuels containing carbonates, taking into account the decomposition of its mineral carbonate part, is as follows (Hamburg et al., 1996):

$$CEF_{oil\ shale} = 10 \times [\, C^r_t + k \times (CO_2)^r_M \times 12 / 44 \,] / Q^r_i \text{ , tC / TJ,}$$

where Q^r_i net calorific value of fuel as received basis, MJ/kg;

C^r_t carbon content of fuel as received basis, %;

$(CO_2)^r_M$ mineral carbon dioxide content of oil shale as received basis, %;

k decomposition rate of carbonates

The formula suggests that the best way to decrease CEF oil shale is to decrease the decomposition rate of the carbonates. The decomposition rate of oil shale carbonates depends on combustion temperature: in combustion technologies at temperatures over 1000°C, $k \approx 1$ (Kull et. al., 1994). It could be reduced at lower combustion temperature (800-850°C).

1.2 Fluidised bed technologies

The fluidised bed technology was originally used in the chemical industry, metallurgy and other industries, but not in power engineering. Two very essential factors gave a push to applying the fluidised bed technology in power engineering. First, it appeared that in the fluidised bed it is possible to burn efficiently low grade fuels, including mining industry enrichment wastes, chemical industry and household wastes or other combustible waste. Secondly, an advantage of the fluidised bed technology is that it enables to decrease the harmful emissions of fuel burning without a need to use very expensive special cleaning equipment of flue gases.

An essential construction element of the fluidised bed furnace is the grate under it, through which air is supplied in the furnace to burn (or gasify) the fuel. The grate differs from an ordinary one used in the grate incinerator furnace, it is simpler in construction and the area of its free cross-section is considerably smaller. The fluidised bed grate forms a preliminary obstacle to the upward stream of air and is necessary for an equal distribution of air on the whole surface of the grate.

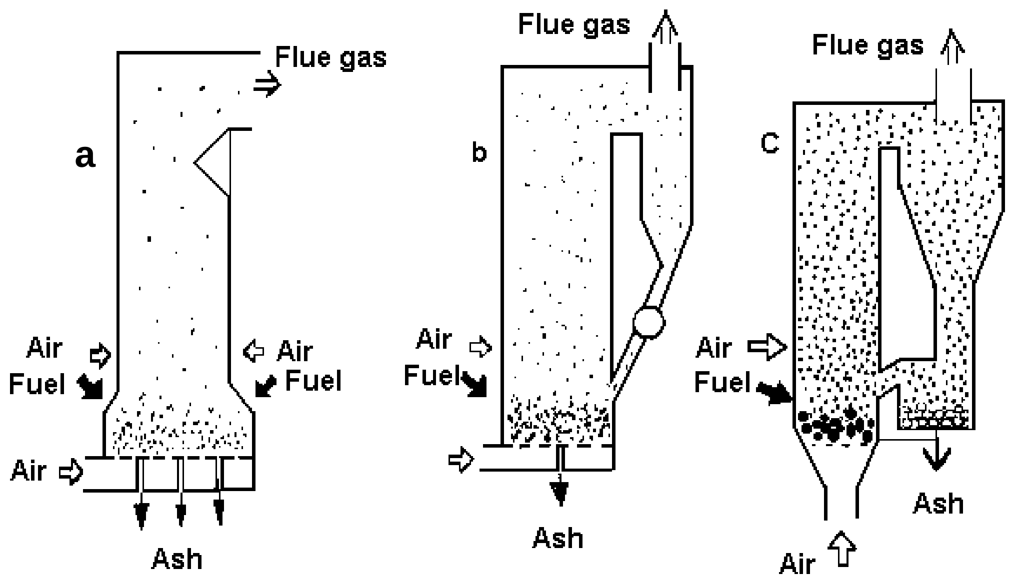
The so-called fluidising of solid particles starts on the grate in case the air velocity is sufficiently high for the fine grain material and the thickness of its layer. The initial velocity of fluidisation is called the *first critical velocity of the fluidisation*. With the further increase in air velocity, the layer expands and the particle flow becomes more intensive. With the further increase in air velocity, a moment will be reached when the particles do not stay in the bed any longer, but are carried out of the bed with air (or gas) – it is the phenomenon of aerotransportation of the particles. The air (gas) velocity corresponding to the start of aerotransportation is called *the second critical velocity of the fluidised bed.*

The fluidised bed between the two critical velocities is also called a pseudofluid bed. Different critical velocities correspond to the particles of different size, specific gravity and shape. The fuels prepared for burning in the fluidised bed contain particles with the diameter from a few micrometers to 10 mm and more. In order to burn most fuels in the fluidised bed furnaces, a so-called carrier bed is needed. For this purpose an inert fine particle material is added, which is fluidised together with the fuel particles. By the moment the air (gas) velocity in the bed reaches that of the first critical velocity that of the largest particles has already exceeded the second critical velocity of the finer particles, i.e., the finer and lighter particles have already left the bed. The situation improves when the specific gravity of the bed material (e.g. sand) is higher than that of the fuel particles. In this case it is sufficient if the carrier bed becomes fluidised. Larger particles which do not participate in the fluidised process will burn floating on the surface of the fluidised bed.

Depending on the velocity of the air stream passing through the fluidised bed the fluidised bed technologies can be divided into the following categories (see Figure 13):

- conventional (bubbling or slow) fluidised bed;
- turbulent (fast) fluidised bed;
- circulating fluidised bed.

Figure 13 Fluidised bed furnaces: a) classical (bubbling or slow) fluidised bed furnace; b) turbulent fluidised bed furnace; c) circulating fluidised bed furnace



Fluidised bed furnaces can operate at either the atmospheric or over pressure. As fluidised bed furnaces operating at the atmospheric pressure are most widespread at present, we shall discuss only these in this chapter.

1.2.1 Conventional fluidised bed furnace operating at the atmospheric pressure

The classical fluidised bed is also called bubbling or slow fluidised bed. In case of this fluidised bed technology, the velocity of air (gas) in the fluidised bed is the lowest since the grate surface is inversely proportional to the air (gas) velocity passing through the bed, then the surface of the grate of a high power energy boiler has to be high (Tampella Power, 1989). In case of the slow fluidised bed, few fuel particles (which have exceeded the second critical velocity) are carried out of the bed and the rest of the fuel mass burns in the fluidised bed. To maintain the temperature of the bed in the desired limits (800–900°C) in most cases it is necessary to place heat transfer surfaces into the bed. One of the advantages of the conventional fluidised bed combustion boiler is that the amount of ash disposed directly from the furnace is considerably bigger than, for example, in case of the circulating fluidised bed boiler.

1.2.2 Turbulent fluidised bed furnace operating at the atmospheric pressure

If the air (gas) velocity in the classical fluidised bed is increased, the replacement of particles in the bed will intensify and the amount of particles carried out of the bed will increase considerably in comparison with the conventional fluidised bed furnace (Altmann, 1989). With the increase of the velocity of the gases in the space above the furnace bed, the time for the fuel particles to stay in the furnace decreases and some of the particles are not burned out in the space of the furnace. The particles of the fully unburned solid fuel (coke) are caught in the cyclone after the furnace and returned to the furnace where they burn out fully. The turbulent fluidised bed furnace can be considered a transition from the conventional fluidised bed combustion boiler to the circulating fluidised bed burner.

1.2.3 Circulating fluidised bed furnaces operating at the atmospheric pressure

In case of circulating fluidised bed furnaces the air (gas) velocity traversing through the grate exceeds twice and more the air velocity in the conventional fluidised bed furnaces. The required grate surface is nearly as many times less (Oil Shale Perspectives..., 1996). For circulating fluidised beds, the velocity of the gases in the bed and that of most fuel particles in the cross-section of the furnace are higher than their second critical velocity, i.e., these particles are carried out of the bed and they fill the whole volume of the furnace. In addition there are particles of ash and coke that get into the furnace due to circulation. This enables an essentially better use of the whole furnace volume both for burning fuel particles and for binding the sulphur components with the carbon components added to the fuel or existing within the mineral part of the fuel.

A disadvantage of the circulating fluidised bed is that some fuel ash particles become too fine in the course of circulation and therefore the ash particle size in the flue gas exiting the hot cyclone is too small. The disintegration of the ash particles separated in the cyclone is conduced by the fact that it is used as a so-called solid heat carrier since a part of the ash is trapped in the cyclone, and after being cooled it is returned to the furnace to maintain the desired temperature there. As a result of disintegration, the mass of fine particle ash not separated from the flue gases or in the connective flue ducts and in the multicyclone increases. The load of the electric (or bag) filters in catching the ash increases critically compared even with the pulverised fuel combustion boilers.

Fluidised bed combustion boilers are characterised by a number of general favourable indicators, the most essential ones being the following:

- Intensive mixing of fuel particles and a high heat transfer factor in the fluidised bed enable to burn fuels of variable quality.
- Due to low combustion temperatures in the fluidised bed (800–900^{o}C), the amount of nitrogen oxides (NO_x) emerging during the combustion process is low and conditions are extremely favourable for binding sulphur oxides (SO_2) in the fuels with the carbon compounds added to the fuel or existing in the mineral part of the fuel. This is why there is no need to install any sulphur catching equipment. Electric or bag filters are only needed to separate solid particles from the flue gases.
- Fluidised bed combustion boilers can be regulated flexibly and in broad limits and it has no essential effect on the efficiency of the boiler.

The companies making fluidised bed combustion boilers have found different design solutions for raising their efficiency, improving their operational reliability and making them more universal.

1.2.4 Pressurised fluidised bed combustion

Pressurised fluidised bed combustion (PFBC) is operated at pressure of 1.0–1.6 MPa. Due to the pressurised conditions and more effective steam production, the combustion chamber of PFBC is generally one-third the size of a conventional furnace. The pressurised gases exiting the combustor are cleaned of particulates, alkali and other contaminants. The gases are then expanded in a gas turbine to generate electricity and passed through an economiser to preheat the feed water for the steam turbine cycle before being discharged to the atmosphere.

1.3 Combined heat and electricity generation

1.3.1 Combined energy generation equipment

The efficiency factors of steam power equipment (net) have reached 38%. Further expected improvements can raise the efficiency factor, according to estimates, up to 44%. An essential increase in the efficiency factor can be obtained with the implementation of electricity generation based district heating. The problem here is that the heat load of district heating systems varies the year round, depending on the outdoor temperature.

Implementation of the equipment with a combined steam and gas cycle allows to improve the efficiency significantly and thus increase electricity production while the amount of hazardous emissions remains unchanged. A steam turbine (ST) and a gas turbine (GT) are combined in one unit. The number of orders on the new power plants with the combined steam and gas cycle equals the orders of steam turbine power plants in the world (see Figure 14).

In 1990–1993 80,000 MW of power plants was ordered, including 1/3 in West Europe and 40% in the Far East.

The efficiency of gas turbines can be improved by raising the temperature of input gases in the turbine. Without cooling the gas turbine blades, the gas temperature may reach 850–900^{0}C and with blade cooling up to 1400^{0}C . The new Westinghouse gas turbine is designed to gas temperature of 1238^{0}C. In this case the efficiency is 58%. In the new MS 9001 H gas turbine of General Electric the temperature of input gases is 1430^{0}C and the electrical net efficiency of the combined cycle is 60%.

1.3.2 Modifications of combined cycles

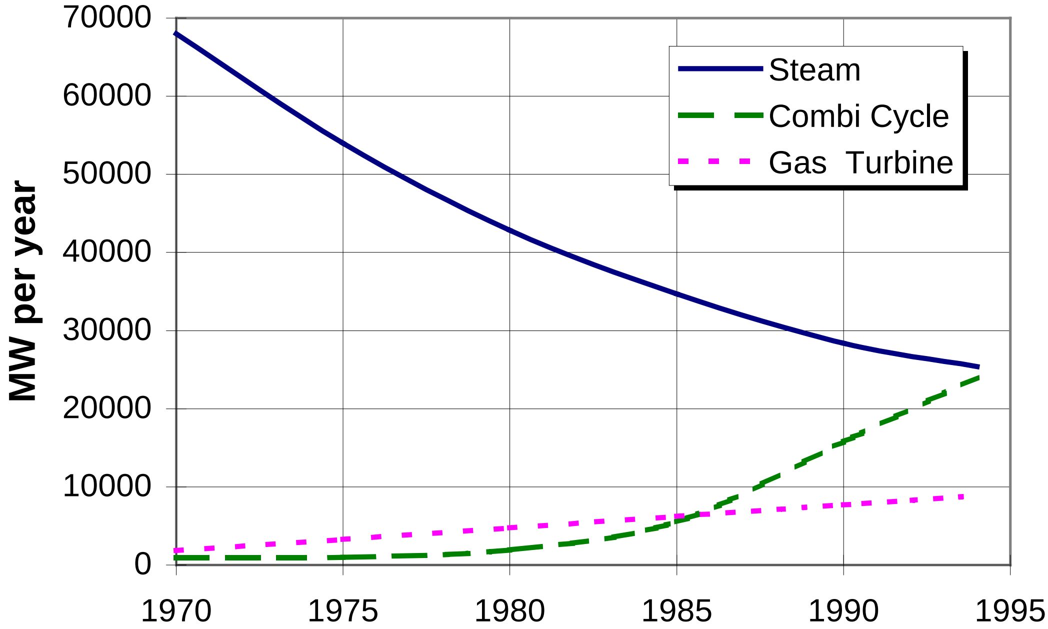
Gas cycle on the steam cycle

In the most widely used modern combined cycle where the electricity efficiency of the new equipment reaches 58–60%, the gas cycle is built on the steam cycle. The heat of the discharged gases from the gas cycle is utilised in the steam cycle. Such a combined cycle is extremely flexible and can be used besides electricity generation for heat production with taking heat directly from the steam boiler or by tapping. The potential layout is rather simple: a single pressure steam cycle or a triple pressure steam cycle with reheating. The final choice depends on technical and economic factors, including mainly price and specification. Any fuel admissible for gas turbines can be used here.

Steam boiler equipped AGS

Gases exiting the gas turbine contain significant amounts of oxygen (up to 15%). They can be utilised as combustion air in an ordinary steam boiler fuelled with any fuel.. In this case the steam boiler requires no air preheater. To lower the temperature of gases exiting the steam boiler, the economiser must be extended and the regenerative preheating of feed water restricted. Usually the auxiliary economiser runs in parallel with regenerative preheaters. Compared with the steam cycle, the efficiency of such a combined cycle increases insignificantly since the increase in the steam cycle efficiency from regenerative preheating of feed water decreases.

Figure 14 Orders on fossil fuel fired heat equipment in the world



STIG-steam injected gas turbine

In the combined gas–steam cycle with the recovery boiler 2/3 of electric power is produced in the gas turbine and 1/3 in the steam turbine. At the same time the cost of the gas turbine makes up only 1/3 of that of the steam turbine. Also such a flow sheet may be used where gas and steam expand together in the gas turbine. Water is evaporated with the residual heat of the gas turbine and the steam is conducted to the combustion chamber of the gas turbine. The capacity of the gas turbine increases since the mass flow through the unit increases while the flow of fuel increases also. The efficiency grows because the heat of gases exiting the gas turbine is utilised..

1.3.3 Large combined cycle plant with CO_2 separation and disposal

In recent years CO_2 separation and disposal have been investigated in combination with several power generation technologies. One of these technologies is the natural gas fired combined cycle plants for district heating. A number of them will be installed in the near future (Inventory of Technologies…, 1995). CO_2 separation can be achieved by commercially available technologies, such as monoethanolamine (MEA) absorption. Such a process enables 90% CO_2 separation. It will have a significant drawback on generating efficiency, which will fall by 8 to 9%.

Investment costs for a combined cycle plant with MEA CO_2 absorption, compression, transport and disposal have been estimated at 1700 US$/kWe; investment costs for a conventional plant would be 750 US$/kWe. Higher generating efficiencies for combined cycle plants cause lower investment costs for CO_2 separation and disposal.

CO_2 from a pulverised coal power plant can be washed out by chemical CO_2 absorption or coal can be burned in an O_2/CO_2 mixture (recycling of flue gas). The latter way has a lower efficiency drop (8%).

2 Possibilities of co-combustion of different fuels in new boiler units

2.1 Objectives of co-combustion of different fuels

It is reasonable to use co-combustion if as a result:

- the ignition and combustion processes become more efficient,
- the amount of harmful emissions in escaping flue gases is reduced,
- the operation conditions of the boiler units improve,
- it is possible to expand the range of fuel selection for combustion in existing boiler units,
- it is easier to adopt new combustion technologies,
- it is easier to adopt indigenous and cheaper imported fuels.

It is possible to succeed in co-combustion if the physico-chemical characteristics of the fuels are taken into account while preparing the mixtures. On the other hand the selection of fuels depends on the existing possibilities. The indigenous fuels in Estonia, which could be considered, are mainly oil shale and peat and to a smaller extent wood (Jaakko Pöyry …, 1994). The only way for expanding the range of applicable solid fuels is with imports.

2.2 Co-combustion of peat and oil shale

Peat and oil shale are indigenous fuels in Estonia. Their co-combustion has not been researched yet. In order to evaluate the possibilities of co-combustion of peat and oil shale, let us examine the physico-chemical characteristics of these fuels in some detail. The parameters of both fuels change within certain limits. Here the comparison is based on the data from the literature (Boilers heat supply, 1973) (Table 17).

Table 17 Comparison of the physical characteristics of peat and oil shale

Source categories	Unit	Peat	Oil Shale
Net calorific value	MJ/kg	8.1	8.6
Ash content	%	6.2	41.2
Moisture content	%	50.0	12.5
Sulphur content	%	0.1	1.4
Volatile	%	70.0	90.0
Carbon and hydrogen ratio	-	9.5	7.63
Carbon emission factor (CEF)	tC/TJ	28.9	29.1/22.0
Sulphur emission factor (SEF)	tS/TJ	0.15	1.65
Mineral carbon dioxide content $(CO_2)_M$	%	-	18.4

One can see (Table 17) that peat and oil shale share the following indicators:

- low calorific value,
- large content of volatile matter,
- the lowest carbon and hydrogen ratio (C/H) of all solid fuels,
- high and practically equal carbon emission factors;

The following indicators are different:

- ash content,
- sulphur content,
- moisture content,
- content of carbonate compounds in the mineral part of the fuel.

The carbonate compounds in the mineral part of oil shale disintegrate at the combustion of the fuel and mineral carbonate dioxide$(CO_2)_M$ is formed. The latter is added to CO_2 formed at the combustion of organic carbon of the oil shale, this results in an increase in the carbon emission factor of oil shale: its value is 22.0 tC/TJ without carbonate $(CO_2)_M$, but at practically total decomposition of the carbonate compounds of the mineral part of oil shale it is 29.1 (Hamburg et al., 1996).

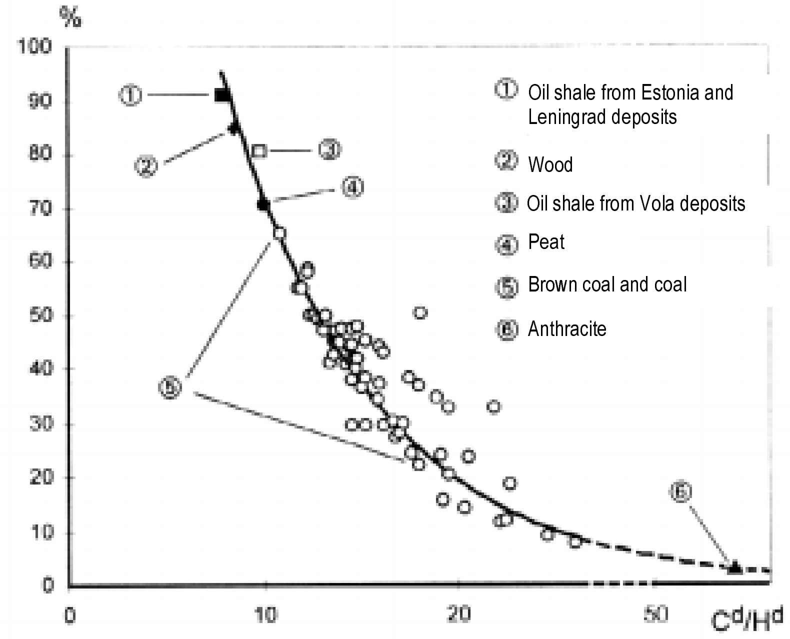
2.2.1 Co-combustion of peat and oil shale in the bubbling fluidised bed

Peat has been successfully burned in the bubbling fluidised bed, but oil shale has not. Combustion of peat in the bubbling fluidised bed is successful for several reasons. The ash content and volume mass of peat are smaller, but the content of volatile matter is high. As a result, only part of the fuel reaches the fluidised bed and in case of the right ratio of primary and secondary pressure it is mainly gasification of the fuel that takes place in the fluidised bed. In this case it is not necessary to install cooling surfaces in the bed and ash is not expected to sinter and slag. The disadvantage is that in case of boilers of lower heat capacity, the peat particles that have not burned up escape from the furnace. When concentrating in the flues and ash collectors they can cause explosions.

The circumstances of oil shale combustion in the bubbling fluidised bed are entirely different from those of peat combustion. Depending on the technologies of preparation for oil shale combustion in the fluidised bed, the course fuel particles account for 20 to 50% of the general mass of the fuel. These particles are gasified and burn up in the fluidised bed. As the ejection and burning of volatile substances is very intensive at the heating of oil shale, then even despite the existence of cooling surfaces in the bed, the local temperature increase in the bed could rapidly reach the level that causes sintering and slagging of the oil shale ash. As a result the normal operation of the fluidised bed is discontinued. Sintering and slagging of the ash in the fluidised bed are further promoted by intensive burning of the volatile substances that had escaped the fluidised bed and small particles that had not reached the bed, above the bed.

There is no experience of co-combustion of peat and oil shale in the bubbling fluidised bed. It is possible to make some assumptions about the character of the combustion process of the mixture, based on the experience of separate combustion of these fuels in the bubbling fluidised bed. If we add peat to oil shale, the volume of combustible fuel in the bed will fall, depending on the amount of peat in the mixture. This is accompanied by an increase in the amount of combustible fuel in the furnace space above the bed at the expense of peat. The temperature in the space above the bed may rise at the intensive co-combustion of combustible gases that have escaped from the burning layer, fine oil shale and peat, and the probability of the melting of the ash particles is high both in the bed and in the space above the bed. The situation could improve if the amount of oil shale in the mixture is substantially reduced.

Figure 15 Volatile matter in the combustible part of fuels depending on the organic carbon and hydrogen ratio



From the point of view of binding the sulphur that is in the fuel, it is not necessary to add oil shale to peat, and if, then only a small amount, as the sulphur emission factor (SEF) is more than ten times smaller than for oil shale. The mineral part of oil shale contains a sufficient amount of carbonate compounds to bind the sulphur in it, for the molar ratio is C/S = 7–8 in oil shale. If C/S = 2.5–3, it is sufficient for the total binding of sulphur.

It is important to compare the characteristics of oil shale, peat and wood (which are the domestic fuels in Estonia) with those of the other solid fuels used for power generation. The relative content of volatile matter in the combustible substances of fuels via the ratio of organic carbon and hydrogen is given in Figure 15. Oil shale, peat and wood differ from other energy fuels in their high volatile matter content. The high volatile matter content of these fuels provides good prerequisites for their combustion and gasification. Due to the low ratio of C^d/H^d the CEF of oil shale without carbonate $(CO_2)_M$ is 22 tC/TJ, but with the total decomposition of the mineral part of oil shale it is 29.1 tC/TJ.

Co-combustion of peat and oil shale allows reduction of the total carbon emission factor. Reduction of the amount of oil shale in the mixture decreases the amount of carbonates $(CO_2)_M$. Some reduction of the carbon emission factor could be achieved at the combustion of the mixtures at lower fluidised bed temperatures if the carbonate mineral part of oil shale does not disintegrate entirely.

Combustion of peat and oil shale mixtures in the bubbling fluidised bed, aimed at power generation, is evidently not reasonable in large Estonian power stations.

2.2.2 Co-combustion of peat and oil shale in the circulating fluidised bed

The circulating fluidised bed is characterised by a high velocity of gases in the whole cross-section of the furnace; as a result the bulk of the fuel particles is carried out of the fluidised bed, uniformly filling the whole space of the furnace. The ash and coke particles that were caught in the cyclone after the furnace are added and they are directed back to the furnace. This enables better use of the whole space of the furnace for the combustion of fuel particles, as well as for binding sulphur particles with the carbonate compounds added to the fuel or existing in the mineral part of the fuel.

The technology of the combustion of the fuel in the circulating fluidised bed is more suitable for the combustion of fuels of higher organic carbon content and lower volatile matter content (coals) .It takes much more time to burn out organic carbon from the fuel particles than it is necessary for the combustion of the particles of the fuels that are rich in volatile substances and have a low organic carbon content. Therefore the direction of the unburned particles (coke) of coals of high organic carbon content back to the furnace is completely justified.

While the combustion of oil shale in the bubbling fluidised bed has been practically impossible, its combustion in the circulating fluidised layer has been successful. This has been confirmed by the combustion tests. The tests also confirm that in the circulating fluidised bed the sulphur compounds, existing in the oil shale, are bound practically 100% with the carbonate compounds of the fuel arising from the gases at combustion. The content of nitrogen compounds is also low in flue gases – 10 to 170 ppm, which is generally characteristic of oil shale combustion. The disadvantage is that ash particles become too fine in the course of the circulation and as a result the ash contained in the gases coming out of the hot cyclone is very fine. The ash is refined also because of its use as a so-called solid heat carrier. Part of the ash caught in the cyclone is directed back to the furnace after being cooled in the fluidised bed. This is aimed at maintaining the desired temperature in the furnace. As a result of the refining process, the volume of ash increases substantially and it does not separate from the flue gas in the convective flues and multicyclones. The load of multistage precipitators (or textile filters) in the collection of fly ash increases critically, even in comparison with the boilers operating at pulverised fuel combustion.

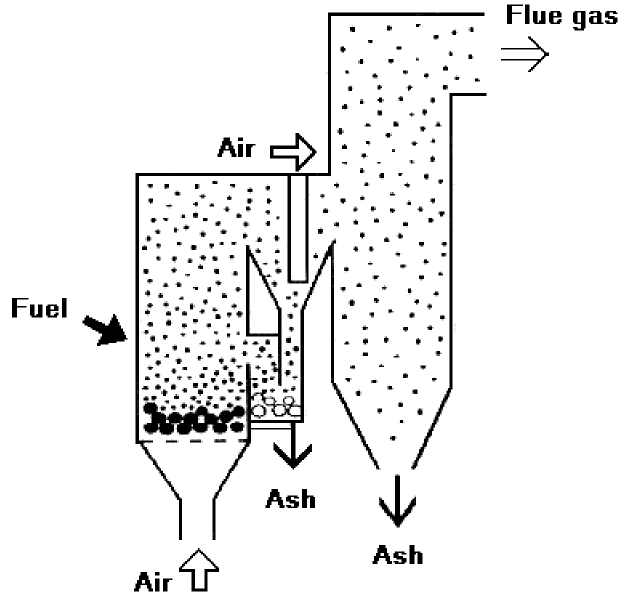
Proceeding from the above-said, the prospects of the co-combustion of peat and oil shale should be good and have little dependence on their mass ratio in the mixtures. The measurements of large boiler units are adequate and the peat and oil shale particles can practically burn up during the one occasion when they are in the furnace. From the position of reducing the chemical incomplete combustion loss (q_3) of the fuel, direction of the peat and oil shale ashes caught in the hot cyclone back to the furnace is not necessary. Cooled and uncooled ashes could be directed back to the furnace if it is not possible to regulate the flame temperature of the furnace to the expected level or it happens to be necessary for better binding of the gaseous sulphur compounds, arising in the combustion of the fuel mixture, in the furnace space. Otherwise it is reasonable to direct most of the ash caught in the hot cyclone and then cooled to the ash removal system. This will improve the operating conditions of the convective heat transfer surfaces of the steam generator. The efficiency of ash collecting equipment is higher in case of smaller amounts of fly ash.

2.2.3 Two-phase combustion with gasification of peat and oil shale in the fluidised bed

The large content of volatile matter in peat and oil shale (see Table 17) necessitates the so-called two-phase combustion of these fuels: with gasification in the bubbling fluidised bed (or near it) and the combustion of arising combustible hot gases in the separate furnace space (Figure 16) (Martins, 1994). While the primary pressure makes up 30–40% of the air necessary for combustion, it is possible to reduce the area of the fire grate substantially in comparison with the bubbling fluidised bed. Heat exchange surfaces are not necessary for the bed, for the heat arising in the combustion of coke and a small amount of volatile matter go on the gasification of the fuel and the temperature of the fluidised bed is easy to adjust with the regulation of the ratio of the fuel and primary pressure. In case of oil shale the fluidised bed is formed of ash, because the ash content of oil shale is high – 40–50%. The fine coke particles that have escaped from the fluidised bed will be separated from the combustive hot gases in the jalousie separator and are directed into the separate fluidised bed for secondary combustion. Part of the fly coke that was directed back will participate in re-circulation. The advantage of the two-phase combustion technique for fuels rich in volatile substances, in comparison with the circulating fluidised bed technique, is the fact that this enables removal of the greater part of the fuel ash (up to 70%) from the pre-gasifier of the fluidised bed. As the accompanying ash amounts are smaller, the operating conditions of the heating surfaces of the boiler should improve and the work of electric filters will be more efficient.

In the two-phase combustion of oil-shale, problems have arisen with the combustion of hot gases. The high temperature of hot gases (ca 800^{0}C) and high combustion activity promote intensive combustion of these gases in small furnace spaces. This brings about high local temperatures near the burners of hot gases or embrasures. The ash particles accompanying hot gases at high temperature melt, causing slagging of the heating surfaces of the furnace. In order to reduce the combustion intensity of the hot gases it is necessary to feed secondary air into the furnace in parts and from different heights of the furnace.

Figure 16. Furnace with pre-gasification fluidised bed



Two-phase combustion of oil shale has been studied on the laboratory testing equipment in the Estonian Energy Research Institute for several years. The maximum heat efficiency of this equipment is 0.2 MW_{th} and that of the industrial steam generator 10 MW_{th} (Martins and Pesur, 1997).

We have studied the two-phase combustion of peat, oil shale, wood and their mixtures in the industrial district heating boiler T-4.5-0.7. A pre-gasifier of the fluidised bed was placed in the fort of this boiler (Martins and Pesur, 1996). We succeeded in the gasification of all the mentioned types of fuel and their mixtures. If we examine separately the two-phase co-combustion of the mixtures of peat and oil shale, then irrespective of the ratio of the fuels in the mixtures, no difficulties were faced in the gasification process. The hot gases were burnt in the furnace of the district heating boiler T-4.7 -0.7. The secondary pressure was directed to the furnace. After completing the test combustion, the renovated boiler started operation in 1994.

When practically 100% of the gases arising from the sulphur compounds existing in the fuel are bound with the carbonate mineral parts of the fuel at the oil shale combustion in the circulating fluidised bed, then in the two-phase combustion of oil shale the figure is a little smaller (95–97%) according to the test reports.

It is possible to reduce CO_2 emission at the two-phase gasification combustion in the fluidised bed of peat and oil shale at the expense of oil shale, since the disintegration stage of the carbonate compounds of the mineral part of oil shale at gasification in the fluidised bed decreases. As a result the emission of carbonate $(CO_2)_M$ is reduced by 20–25%. The decrease in the total $(CO_2)_M$ emission depends on the ratio of peat and oil shale in the mixture. If peat is prevailing in the mixture, then the decrease of total $(CO_2)_M$ is smaller and vice versa.

Although the introduction of the two-phase combustion technology is not especially complicated in the oil shale fired power stations (the hammer mills of the existing steam generators should be replaced by pre-gasifiers of the fluidised bed of the fuel), before adoption preliminary checking in larger boiler units (50–100 MW_{th}) is required; however, this is unlikely to occur at the moment.

2.3 Co-combustion of coal and oil shale

Coal is not extensively used in Estonia so far (2.4 PJ in 1996). It has mainly been burned in small district heating boiler houses. If the physico-chemical characteristics of peat and oil shale can be regarded as almost stable, the respective figures for coal vary within a wide range (e.g. the content of volatile substances, see Figure 15), depending on the location of the coal deposit. Sulphur emission factors of Donetsk and Kemerovo coal differ nine times (see Table 18) (Boilers heat supply, 1973). This must be taken into account at the combustion of coal and oil shale mixtures. The large carbonate content in the mineral part of oil shale gives hope that even coal with high sulphur content can be successfully burned with oil shale, guaranteeing the required sulphur binding level.

Table 18 Comparison of different coal types

Parameter	Unit	Coal deposit	
		Donetsk	Kemerovo
Net calorific value	MJ/kg	17.54	26.13
Ash content	%	34.6	11.0
Moisture content	%	9.0	8.5
Sulphur content	%	3.2	0.5
Volatile content	%	42.0	40.0
Carbon and hydrogen ratio (C/H)	-	14.19	14.0
Carbon emission factor (CEF)	tC/TJ	25.1	25.3
Sulphur emission factor (SEF)	tS/TJ	1.8	0.2
Mineral carbon dioxide content $(CO_2)_M$	%	-	-

2.3.1 Co-combustion of coal and oil shale in the bubbling fluidised bed

Co-combustion of coal and oil shale in a renovated industrial district heating boiler E-1.0-OP-2 (0.6 MW_{th}) was studied in the Estonian Energy Research Institute. The most significant aim of the co-combustion of coal and oil shale was to study the reduction of the content of waste gases SO_2 and NO_x in the burning products.

Starting the fluidised bed boiler at the combustion of coal and oil shale mixture turned out to be much easier than starting it with only coal. When starting the boiler with coal the temperature had to be raised to at least 700°C, with coal and oil shale mixture the boiler started without any difficulties already when the temperature of the bed reached 350–400°C.

Table 19 presents the testing data of coal and a mixture of coal and oil shale. The sulphur dioxide and nitrogen dioxide contents of the escaping flue gases are indicated both for coal combustion and co-combustion.

Table 19 Test data on the co-combustion of coal and oil shale

Fuel	Content			Calorific value	Gaseous emissions		
	A^r, %	$(CO_2)^r_M$, %	S^r	Q^r_i, MJ/kg	SO_2^*, mg/mn^3	NO_x^*, mg/mn^3	CO_2*, g/kW·h
Coal	24.45	1.31	0.78	24.18	541-724	291-760	505.4
Coal and oil shale mixture	41.95	10.18	1.29	14.51	301-511	180-255	445.6

* at the calculated excess air factor 1.5
A^r ash content of fuel as received basis, %
$CO_2)_M$ mineral carbon dioxide content of fuel as received basis, %;
S^r sulphur content of fuel as received basis, %
Q^r_i net calorific value of fuel as received basis, MJ/kg.

We can see (Table 19) that at the co-combustion of coal and oil shale the SO_2 content in the flue gases has decreased 1.4–1.8 times in comparison with its contents in the flue gases at coal combustion. The NO_x content fell 2.3 times as an average. The reduction of CO_2 in flue gases was not very high, but noticeable (Table 19). One essential reason for CO_2 reduction in flue gases was a low decomposition rate (k = 0.2–0.3) of oil shale carbonates.

The tests confirmed the advantages of co-combustion of coal and oil shale in the bubbling fluidised bed. It should be taken into account that the oil shale content in the mixture should not exceed ca 30%. While burning mixtures with a higher oil shale content, unfavourable phenomena arose, which occurred only at the combustion of oil shale in the bubbling fluidised bed. Co-combustion of coal and oil shale mixtures in large boiler units, using the bubbling fluidised bed technology, is in principle feasible, although it has some design difficulties.

2.3.2 *Co-combustion of coal and oil shale in the circulating fluidised bed*

There is an extensive experience in the combustion of different types of coal in the circulating fluidised bed boiler units and therefore it is not reasonable to discuss it here. Testing oil shale combustion in the circulating fluidised bed has also proved successful. Consequently the co-combustion of the mixtures of these fuels should be successful in the circulating fluidised bed. Nevertheless the final answer could be given only after test combustion. When burning coal alone in the circulating fluidised bed, limestone should be added in order to bind the sulphur existing in the coal. This is not necessary in the co-combustion of the mixtures of coal and oil shale.

Co-combustion of coal and oil shale mixtures in the circulating fluidised beds may be regarded as one of the best possible solutions (and not only in Estonia) if there are economic and technical facilities available.

2.3.3 *Co-combustion of coal and oil shale with gasification in the bubbling fluidised bed*

As we could see above, it is easy to gasify oil shale with air in the bubbling fluidised bed. Because of the low content of volatile matter in coal, gasification of this fuel is not feasible in the classical boiling layer. Coal like oil shale coke must be burned in the fluidised bed. In this case the required area of the fluidised bed for secondary combustion must be expanded and provided with the heat exchange surfaces. The combined combustion technology of coal and oil shale with gasification in the bubbling fluidised bed cannot be suggested as an alternative today, since this is a solution that has not been tested at all.

2.4 Other co-combustion possibilities

From other co-combustion possibilities of fuels the following could be discussed:

- oil shale and wood,
- peat and wood.

Residual wood could be burned with the aim of power generation. There are remarkable amounts of residual wood in Estonia after felling of trees and in woodworking. Wood combustion combined with other fuels will enable total reduction of CO_2 emission.

Table 20 gives a brief survey of possible implementation of various co-combustion technologies for burning different fuels.

3 Conclusions

Today 98.5% of electricity in Estonia is produced by pulverised oil shale combustion. The efficiency of Estonian power plants is low (27–29%). However, it is quite likely that Estonia will continue to use oil shale for the generation of electricity in the future and the combined use of peat with oil shale is not excluded. This could contribute to the security of supply and allows maintenance of independence from imported energy resources. Intensive use of oil shale for energy production in the future requires considerable improvement of the existing power plants. Among the main targets are the following: to increase the efficiency of power plants, to reduce the level of CO_2 and SO_2 emissions to internationally acceptable values, and to improve ash removal. From the point view of GHG emissions, it is important to note that during the combustion of pulverised oil shale CO_2 is not formed only as a burning product of organic carbon, but also as a decomposition products of the carbon part of ash. Therefore the total quantity of carbon dioxide increases up to 20% in flue gases of oil shale. To solve these problems SE Eesti Energia is planning to study the feasibility of the circulating fluidised bed (CFB) combustion technology for burning oil shale to replace the pulverised combustion (PC) technology. The CFB combustion technology enables to increase the efficiency of SO_2 capturing and facilitates substantial reduction in the decomposition rate of carbonates in the mineral part of oil shale and that of CO_2 content in flue gases of oil shale power plants.

The possible combustion technologies for burning oil shale, peat, coal and their mixtures are:

1. Bubbling fluidised bed

   In case of oil shale a moderate decrease in CO_2 emissions could be achieved due to the more efficient combustion and lower decomposition rate of the carbon part of oil shale ash. At the combustion of oil shale and peat mixture CO_2 emissions could be reduced only for lower fluidised bed temperatures where the mineral part of carbon in oil shale does not disintegrate completely. Complete reduction of SO_2 emissions is guaranteed. It is one way to introduce domestic fuels.

Table 20 Co-combustion of different fuels (summary)

Fuel	Combustion technology	Advantages	Problems	Investment cost (US$/kW$_e$)	Cost of CO_2 reduction (US$/t$CO_2$)
Peat and oil shale	Bubbling fluidised bed	A moderate decrease in CO_2 emissions could be achieved, because of higher efficiency of combustion and lower decomposition rate of oil shale ash carbon part. Complete reduction of SO_2 emissions is guaranteed. It is one way to adopt domestic fuels.	Difficulties in regulating the temperature in the fluidised bed and in freeboard. A grating with a larger area is required.	1650-2200	15-25
	Circulating fluidised bed	Considerable decrease in CO_2 emissions could be achieved, because of higher efficiency of combustion and lower decomposition rate of oil shale ash carbon part. Combustion conditions of peat and oil shale are good and depend little on their weight ratio in the mixtures. Complete reduction of SO_2 emissions is guaranteed. It is a good way to adopt domestic fuels.	Intensive refining of the ash increases critically the load of multistage precipitators (or textile filters) if the oil shale content is over 50% in the mixture.	1500-1960	13-22
	Two-phase combustion with gasification in the fluidised bed	Considerable decrease in CO_2 emissions could be achieved because of higher efficiency of combustion and lower decomposition rate of oil shale ash carbon part. Gasification conditions of peat and oil shale are very good and depend little on their weight ratio in the mixtures. Sufficient reduction of SO_2 emissions is guaranteed. It is a good way to adopt domestic fuels.	Slag-forming problems of fly ash in the furnace. The situation could completely improve with distribution of secondary air injections.	1350-1760	11-19
Coal and oil shale	Bubbling fluidised bed	A moderate decrease in CO_2 emissions could be achieved, because of higher efficiency of combustion and lower decomposition rate of oil shale ash carbon part. Complete reduction of SO_2 emissions is guaranteed. It is one way to use cheaper imported fuels with domestic fuels.	Oil shale content in the mixture should not exceed 30%. A grating with a larger area is required.	1500-2000	12-21
	Circulating fluidised bed	Considerable decrease in CO_2 emissions could be achieved, because of higher efficiency of combustion and lower decomposition rate of oil shale ash carbon part. Complete reduction of SO_2 emissions is guaranteed. It is the best way to use cheaper imported fuels with domestic fuels.	Intensive refining of the ash increases the load of multistage precipitators (or textile filters).	1360-1800	10-18
	Two-phase combustion with gasification in the fluidised bed	Considerable decrease in CO_2 emissions could be achieved. Complete reduction of SO_2 emissions is guaranteed.	Oil shale content in the mixture must be higher than 80%.	1220-1600	8.5-10

It is possible to burn oil shale and imported coal in large boiler units using the bubbling fluidised bed technology, although it has some problems: first, heat exchange surfaces should be installed in the bed and second, a grating with a large grate area is required. When burning a mixture of coal and oil shale, the share of oil shale in the mixture should not exceed 30%.

2. Circulating fluidised bed

   Considerable decrease in CO_2 emissions could be achieved, due to the better combustion efficiency and lower decomposition rate of the carbon part of oil shale ash. Combustion conditions of peat and oil shale and their mixtures are good and have little dependence on their weight ratio in the mixtures. Complete reduction of SO_2 emissions is guaranteed. It is a good way for introducing domestic fuels and the best possible solution (and not only in Estonia) for the co-combustion of coal and oil shale and it may be taken into consideration if there are economic and technical facilities available.

   A problem is intensively increasing disintegration of oil shale (and coal) ashes loading critically the multistage precipitators (or textile filters) when the oil shale content exceeds 50% in the mixture.

3. Two-phase combustion with gasification in fluidised bed

   A considerable decrease in CO_2 emissions could be achieved due to better combustion efficiency and lower decomposition rate of the carbon part of oil shale ash. Gasification conditions of peat and oil shale are very good and have little dependence on their weight ratio in the mixtures. Sufficient reduction of SO_2 emissions is guaranteed. It is a good way to introduce domestic fuels (oil shale and peat). The problems are slag formation from fly ash and regulation of the combustion temperature in the furnace.

   In conclusion we can say that the best combustion technology for power generation in Estonia is the circulating fluidised bed method. It enables to decrease the CO_2 and SO_2 emissions. Estonian domestic fuels - oil shale, peat and their mixtures could be also used, and if necessary imported coal could be added.

The Influence of Oil Shale Combustion Technology on Carbon Dioxide Emission

1 Introduction

Oil shale is the most important domestic fuel for Estonia. In 1996 the total primary energy supply in the Republic of Estonia was 226.268 PJ. Oil shale production amounted to 133.8 PJ in the same year. Its share in the Estonian energy balance is 59.1%. Estonia has very big oil shale resources – active resources are approximately 1.2–1.3 Gt and passive resources about 4 Gt. The quality of oil shale depends on production technology, which determines also the ratio of organic and mineral carbon in the fuel. Oil shale is produced in three open pits and in six underground mines. Other domestic fuels (mostly peat and wood) account for 9% in the total energy balance.

Approximately 99% of electrical power in Estonia is produced in four oil shale fired power plants with total electrical capacity 3060 MW_e. In 1996 the consumption of oil shale for electrical production was 13 Mt and gross electrical power generation was 9.102 TW•h. Two of the four most powerful oil shale power plants are the Baltic Power Plant (built in 1959–1965; capacity 1390 MW_e) and the Estonian Power Plant (built in 1969–1973; capacity 1610 MW_e.) The Baltic, Kohtla-Järve (39 MW_e) and Ahtme (20 MW_e) plants are combined power plants and also produce thermal power for district heating of the towns of Narva, Kohtla-Järve and Ahtme.

Oil shale mining and production of electrical power are the most important branches in the Estonian economy. Oil shale as a domestic fuel also contributes to the energy supply security and independence from imported fuels. There is no doubt that Estonia will continue to use oil shale for electrical and thermal power production in the future.

In 1996 the share of carbon dioxide emission from oil shale fired power plants was approximately 72% of the total amount emitted from burning fuels. Therefore, reduction of carbon dioxide emissions from oil shale power plants is a very important issue. This is connected with introducing new technologies of oil shale combustion.

In power plants oil shale is burnt using the pulverised firing (PF) technology. The average net efficiency of power plants is relatively low — 27–29% — due to low steam parameters and damping of equipment. Keeping in view environmental protection, the main problems are connected with high emission of sulphur dioxide (10–19 g/kW·h) and large amounts of fly ash (12–20 g/kW·h). The emission of NO_x (1.1–1.5 g/kW·h) is not serious thanks to a very low nitrogen content in the organic part of oil shale. The emission of carbon dioxide (1350–1400 g/kW·h) is a very specific problem.

The Estonian oil shale belongs to the carbonate class. Mineral carbon of the inorganic part of oil shale is added to the organic carbon. The mass ratio of organic carbon and organic hydrogen in the Estonian oil shale is close to that for liquid fuels. CO_2 emission from organic carbon is much lower compared to coals. Depending on the quality of oil shale the share of mineral carbon is in the range 20–30% of the total carbon content.

The ratio of the organic and the mineral carbon dioxide in oil shale combustion products (flue gas) depends on the fuel combustion technology and burning regimes. Consequently the CO_2 emission is not determined only by the primary energy conversion efficiency (the primary energy need for electrical power production) but also by the absolute concentration of carbon dioxide in combustion products.

The equipment of oil shale power plants requires renovation in the near future. Simultaneously new fuel burning technologies should be introduced to increase the net efficiency and decrease SO_2 and CO_2 emission.

The main objectives were to analyse the influence of the combustion technology of the Estonian oil shale on CO_2 concentration in combustion products like greenhouse gas and to develop the corresponding mathematical calculation methods. A detailed analysis of oil shale burning technologies, which influence the carbon dioxide formation mechanism, will be presented. Those technologies are conventional pulverised oil shale firing (PF) technology, utilisation of oil shale in circulating atmospheric fluidised bed combustors (CAFBC) and oil shale burning technology in pressurised fluidised bed combustors (PFBC).

2 The influence of parameters on CO_2 emission

The mass of carbon dioxide (kg) formed in thermal power plant per unit of generated electrical power (kW h) is expressed by the following formula:

$$m_{CO_2} = b\rho_{CO_2} V_{CO_2}\text{, kg/kW·h,} \tag{1}$$

where

b specific consumption of fuel as received basis for the production of a unit of electrical power, kg/ kW·h;

ρ_{CO_2} carbon dioxide density in normal conditions (0°C and 0.1013 MPa), kg/m^3;

V_{CO_2} volume of carbon dioxide in normal conditions formed at the combustion of fuel as received basis per unit of fuel, m^3/kg.

Carbon dioxide emission on the given interval of time is expressed as:

$$M_{CO_2} = 10^{-3} E m_{CO_2}\text{, t,} \tag{2}$$

where

E electrical power production in the power plant (kW·h).

Two parameter groups (formula (1)) determine the specific emission of CO_2 in the power plant. The first group describes the conversion efficiency of fuel energy into electrical power and is expressed as b in formula (1). Parameters of this group are determined first by the energy conversion processes and expressed as the power plant efficiency. The specific consumption of fuel and heat depending on the power plant efficiency is expressed as:

$$b = \frac{1}{Q_l^r \eta}, \text{ kg/kW·h,} \qquad q = b\,Q_l^r, \text{ MJ/kW·h} \qquad (3)$$

where

Q_l^r lower heating value of fuel as received, kW·h/kg or MJ/kg;

η power plant net efficiency.

The power plant net efficiency η is defined as the ratio of the produced electrical power to the potential energy freed in the fuel combustion process. The actual energy freed at fuel combustion may to a certain extent differ from the fuel potential energy due to the losses at burning.

The main component in the power plant net efficiency is the feasibility of energy conversion in the power generating cycle. This is expressed on the basis of the second law of thermodynamics by energy conversion efficiency in power generating cycle (thermal efficiency of cycle). The thermal efficiency of cycle depends on the type of energy conversion cycle (for instance, Rankine's, Brayton's cycles, etc.) and on the parameters of the working fluid. The net efficiency of the power plant depends also on the efficiency of the boiler and heat exchangers and the auxiliary needs.

The properties of the fuel used in the power plant form the second group of parameters influencing the carbon oxide emission. Among these properties the carbon content and the extent to which it is converted to carbon dioxide in the burning process are the most important. These are designated by V_{CO_2} in formula (1).

The carbon in the fuel consists of two parts —organic carbon and mineral carbon—. The organic carbon is bound in the organic part (with organic matter molecule) of fuel and it goes mostly into combustion products as CO_2 generated in the exothermic reaction with oxygen. Part of the organic carbon does not burn completely (very low quantities with modern combustion technologies) or oxidises to carbon monoxide. Consequently the carbon dioxide concentration in flue gas is to some extent lower according to the following stoichiometric equation:

$$C + O_2 \Rightarrow CO_2$$

The efficiency of carbon combustion depends mainly on the following three factors: fuel properties, fuel burning technology and combustion regime.

The mineral carbon is bound with the inorganic matter of the fuel and occurs as a rule as CO_2 in the minerals of carbonates. The Estonian oil shale belongs also to this category of fuels. During the combustion process of fuels of this type the CO_2 formed consists of two parts: carbon dioxide generated from organic carbon in the oxidising process (organic CO_2) and carbon dioxide that is formed at the decomposition processes of minerals of carbonates (mineral CO_2). It is characteristic of fuels containing carbonates that the amount of organic carbon is presented as pure carbon but the mineral carbon quantity is expressed as the amount of carbon dioxide – $(CO_2)_k$.

The quantity of organic and mineral CO_2 in the flue gas depends on the ratio of organic and mineral carbon in the fuel. The carbon dioxide concentration in combustion products formed from the organic carbon of the fuel is very slightly affected by the fuel burning technology. On the contrary, the fuel burning technology has a remarkable influence on the CO_2 amount emitted from the mineral part of the fuel.

The emission of mineral carbon dioxide depends greatly on the behaviour of carbonates in the combustion process of the fuel. The amount of CO_2 freed from carbonates depends on the thermal dissociation of carbonates and also on its direct reactions with gaseous components in flue gas or with other minerals (for instance, sandy-clay minerals). The reaction type depends on the partial pressure of carbon dioxide in flue gas. This, in turn, is determined by the equilibrium pressure of CO_2 at thermal dissociation of carbonates. The equilibrium pressure of CO_2 increases with increasing temperature. The carbon dioxide pressure in flue gas depends on the amount of CO_2 arising in fuel combustion, the fuel/oxygen ratio and the total environmental pressure.

3 Characterisation of the Estonian oil shale

The Estonian oil shale (kukersite) belongs to the class of carbonate fuels. It occurs as a sapropelite deposit characterised by a low carbon/hydrogen ratio in its organic matter.

The Estonian oil shale is a solid fuel with a very high content of mineral matter (60-75% in dry mass), moderate moisture content (9–12%) and low heating value, its lower heating value (LHV) as received basis is 8–10 MJ/kg. Approximately half of the mineral matter of oil shale is in the carbonate form.

The Estonian oil shale deposits lie in the earth's surface in layers. In oil shale layers the organic matter is closely interlaced with sandy-clay minerals (sandy-clay matter). Oil shale layers are separated mostly by seams containing limestone (calcite). In the upper layers of oil shale also separate limestone formations can be found. Oil shale and limestone layers are shown in Figure 17. Oil shale layers are marked in capital letters starting from the lowest layer.

The maximum number of oil shale layers is eight. Towards the south the number of oil shale layers decreases. The maximum total thickness of the oil shale deposit is approximately 5 m, from which the total thickness of the oil shale layers is about 2.5–2.8 m.

Solid fuel mass as received basis consists of the following three constituents (in mass %): moisture (W^r), organic part (R^r) and mineral part (M^r). Obviously:

$$R^r + M^r + W^r = 100\,\% \tag{4}$$

As mentioned above, the inorganic matter of the Estonian oil shale consists of two components: sandy-clay matter, T, and carbonate matter, K. Thus, oil shale as received basis may be observed as a mixture consisting of four different components and expressed as the sum:

$$R^r + T^r + K^r + W^r = 100\,\% \tag{5}$$

Table 21 gives the chemical composition of organic and inorganic matter (sandy-clay and carbonate parts) and Table 22 the mineralogical composition of the carbonate and sandy-clay matter of oil shale.

Figure 17 The Estonian oil shale deposit

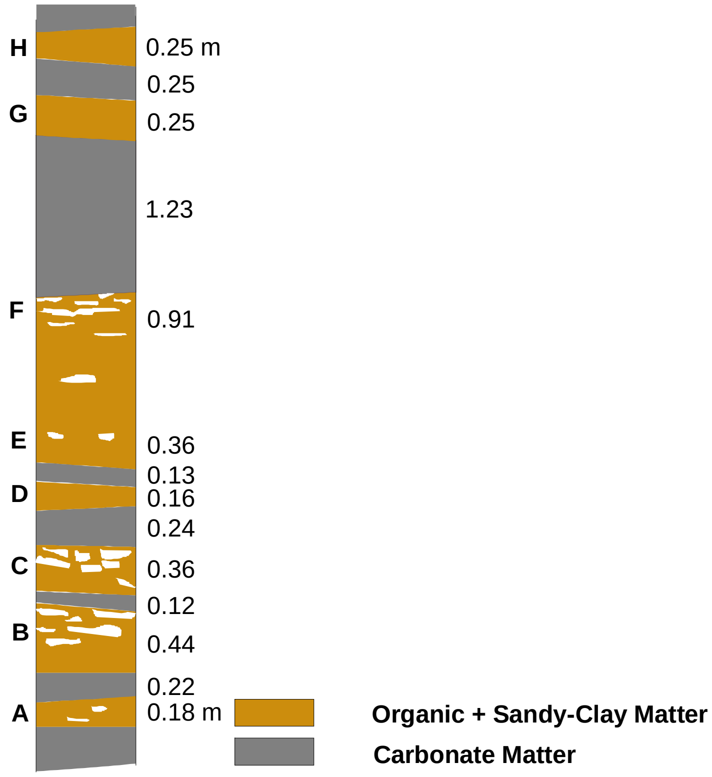


Table 21 Chemical composition of the Estonian oil shale components

Organic matter		Sandy-clay matter		Carbonate matter	
Component	Amount, %	Component	Amount, %	Component	Amount, %
C	77.45	SiO_2	59.2	CaO	53.5
H	9.70	CaO	0.7	MgO	2.0
S	1.76	Al_2O_3	16.3	FeO	0.2
N	0.33	Fe_2O_3	2.8	CO_2	44.3
Cl	0.75	TiO_2	0.7		
O	10.01	MgO	0.4		
		Na_2O	0.8		
		K_2O	6.3		
		FeS_2	12.3		
		SO_3	0.5		
Total 100.00		Total 100.0		Total 100.0	

The content of carbon in the organic part of oil shale is low (77.45%) and the oxygen and carbon mass ratio is 0.13. The most characteristic features of the Estonian oil shale are a high content of hydrogen (9.70%) and oxygen and a low content of nitrogen (0.3%) in the organic part. The C/H mass ratio is approximately 8 and it is close to liquid fuels. Due to the high C/H mass ratio the yield of volatile matter from the organic part is very high being in the range 85–90%. Sulphur content in the organic part (organic sulphur) of oil shale is approximately 1.8%. Chlorine combined with organic matter (0.75%) is one of the peculiarities of the Estonian oil shale.

The HHV (higher heating value) of oil shale organic matter is 36.6 MJ/kg and its LHV is 34.3 MJ/kg.

Table 22 Mineralogical composition of carbonate and sandy-clay parts of the Estonian oil shale

Groups of minerals	Minerals	Formula	Amount, %
Carbonates	Calcite	$CaCO_3$	90.5
	Dolomite	$CaMg(CO_3)_2$	9.2
	Siderite	$FeCO_3$	0.3
			Total:100.0
Sandy-clay	Quartz	SiO_2	23.2
	Rutile	TiO_2	0.7
	Orthoclase	$K_2O{\cdot}Al_2O_3{\cdot}6SiO_2$	28.1
	Albite	$Na_2O{\cdot}Al_2O_3{\cdot}6SiO_2$	5.8
	Anortite	$CaO{\cdot}Al_2O_3{\cdot}2SiO_2$	1.4
	Hydromuscovite	$[K_{1-x}(H_2O)_x{\cdot}Al_3Si_3O_{10}(OH)_2]_2$	23.0
	Amphibole	$[NaCa_2Mg_4(Fe, Al)Si_8O_{22}(OH)_2]_2$	2.0
	Marcasite	FeS_2	12.0
	Limonite	$Fe_2O_3{\cdot}H_2O$	2.8
	Gypsum	$CaSO_4{\cdot}2H_2O$	1.0
			Total:100.0

The main component of the carbonate part is calcium oxide. The average CaO/MgO mass ratio is 27. In some layers near the ground it may be lower.

The average statistical ratio of the mass of oxides to the amount of the CO_2 in the carbonate part of oil shale is $MO_k/CO_2 = 1.257$.

Quartz, aluminium oxide, marcasite and potassium oxides are the essential components of the sandy-clay matter. The quantity of K_2O is about 12 times as big as the amount of Na_2O.

The inorganic matter of the Estonian oil shale does not contain chlorine, but chlorine is a constituent of the organic matter.

Calcite is the main mineral in the carbonate constituent of oil shale. The constituents of the sandy-clay part are quartz, feldspars (mainly as orthoclase) and hydromicas (mainly as hydromuscovite).

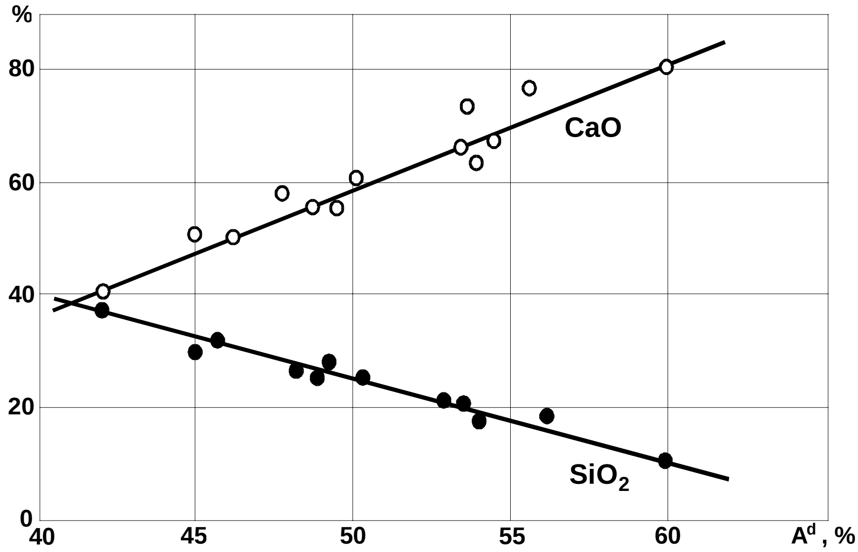
The total sulphur content in dry mass of the Estonian oil shale is in the range 1.5–1.7%. The Ca/S molar ratio is in the range 8–10.

Pyrite sulphur in the Estonian oil shale is presented as marcasite crystals. The amount of sulphate sulphur does not exceed 10% from the total sulphur.

The oil shale utilised at power plants has the following proximate composition as received basis: moisture – 11–12%, ash – 45–48%, carbonate carbon dioxide – 17-19%, LHV – 8–8.5 MJ/kg. The approximate ratio between organic, sandy-clay and carbonate parts in dry mass of oil shale is 35, 25 and 40%.

The mineral matter inherent/extraneous ash mass ratio in the oil shale and also its chemical and mineralogical composition determine the dependence of CaO and SiO_2 in ash on the ash quantity in the fuel. This is illustrated by Figure 18, which shows the dependence of CaO and SiO_2 mass percentage in laboratory ash of the Estonian oil shale on the ash quantity in dry mass. If the amount of ash rises, SiO_2 percentage in ash will decrease, while CaO quantity will increase. The origin of oil shale causes this kind of SiO_2 and CaO dependence in ash on ash percentage because calcium oxide in fuel is bound with extraneous mineral matter. Because calcium oxide in fuel is bound with extraneous mineral matter, as in oil shale, the CaO content in the particles will increase and the amount of quartz will decrease with increasing particle sizes.

Figure 18 Dependence of CaO and SiO_2 content in laboratory ash on the ash content in the Estonian oil shale dry mass



4 Determination of carbon dioxide concentration in combustion products

In normal conditions the volume concentration of carbon dioxide in the combustion products that originate from burning fuels containing carbonate minerals per 1 kg fuel as received basis is expressed by the following formula:

$$V_{CO_2} = 0.01866 \varphi C^r + 0.00509 k_{CO_2} (CO_2)_k^r, m^3/kg, \tag{6}$$

where

φ carbon conversion efficiency to carbon dioxide ;

C^r carbon content in fuel as received basis, %;

k_{CO_2} carbonates decomposition rate;

$(CO_2)_k^r$ mineral carbon dioxide content in fuel as received basis, %.

The following method for the calculation of CO_2 concentration in combustion products is based on proximate analysis of oil shale. The proximate analysis involves the following three components: moisture (*W*), laboratory ash (*A*) and mineral carbon dioxide ($(CO_2)_k^r$).

Proceeding from the proximate analysis of oil shale as received basis its combustible part is expressed by the following formula:

$$P^r = 100 - A^r - (CO_2)_k^r - W^r \ , \%. \tag{7}$$

Formula (7) should be corrected if the sum $A^r + (CO_2)^r_k$ is equivalent to the mineral matter content in the oil shale. In reality besides thermal dissociation of carbonates also association and decomposition reactions between components of the sandy-clay and carbonate parts occur in the ash formation processes at atmospheric pressure. Also chemical reactions between the organic and the inorganic part of oil shale are possible. This is the reason why the sum of the quantity of laboratory ash and the amount of mineral CO_2 does not correspond to the quantity of mineral matter in the oil shale sample. So the direct use of equation (7) for the calculation of the combustible part of the oil shale in not correct. The combustible part of the oil shale calculated using formula (7) is the apparent combustible part of the fuel.

The main chemical reactions that take place in laboratory ash formation processes at atmospheric pressure and cause the mass change in the inorganic part of the oil shale are the following.

Thermal dissociation of carbonates (for instance, dissociation of calcite):

$$CaCO_3 \Rightarrow CaO + CO_2 \tag{8}$$

Oxides originating from the dissociation react with sulphur dioxide and oxygen forming calcium sulphate by the reaction:

$$CaO + SO_2 + ½\, O_2 \Rightarrow CaSO_4 \tag{9}$$

Pyrite (marcasite) sulphur reacts with oxygen by the reaction:

$$4FeS_2 + 11O_2 \Rightarrow 2Fe_2O_3 + 8SO_2 \tag{10}$$

Besides pyrite also organic sulphur is a source of sulphur dioxide.

In addition to the above-mentioned reaction also volatilisation of some components from the mineral matter, separation of crystalline water etc. may take place.

Proceeding from the chemical reactions taking place at ash formation and the extent of those processes it is possible to compile the mass balance of the incineration process and to calculate the ash mass correlating to the primary inorganic matter mass in the fuel (with a certain degree of accuracy). The amount of ash calculated in this way is the corrected ash of fuel.

Using the corrected ash and correlated combustible matter conception the composition of oil shale matter as received basis is expressed as:

$$P^r_c + A^r_c + (CO_2)^r_k + W^r = 100\ \%, \tag{11}$$

$$R^r + S^r_p + A^r_c + (CO_2)^r_k + W^r = 100\,\%. \tag{12}$$

The sum of organic matter and pyrite sulphur (S_p) is equal to the combustible matter content in the fuel. The difference between the amount of laboratory and corrected ash is positive and is expressed by the following formula for the dry mass of fuel:

$$\Delta A^d = \left[0{,}375(1 - a\,\beta_{p.A}) + \beta_{p.A}\right] S^d_p + 2{,}5\,\beta_{S.A}(S^d_p + S^d_o) + (1 - k_{CO_{2A}})(CO_2)^d_k\, , \% \tag{13}$$

Here:

S_p^d pyrite sulphur content in the dry mass of fuel, %;

S_o^d organic sulphur content in the dry mass of fuel, %;

$(CO_2)_k^d$ mineral carbon dioxide content in the dry mass of fuel, %;

$\beta_{p.A}$ pyrite sulphur remaining factor in ash;

a number of atoms in iron sulphide;

$\beta_{S.A}$ factor of conversion of combustible sulphur to sulphate;

$k_{CO_{2k}}$ decomposition rate of carbonate minerals in ash.

The first term $[(0.375(1-a\beta_{p.A})+\beta_{p.A})S_p^d]$ in formula (13) expresses the increasing of the ash mass in the fuel incineration process according to the stoichiometric formulas (9) and (10). The value of this term depends on the amount of pyritic sulphur in the fuel and its remaining factor. The experiments showed that from the total amount of pyrite sulphur in sulphide form in ash an average of 4% remains, i.e. the pyrite sulphur remaining factor in ash $\beta_{p.A}$ = 0.04.

Theoretical calculations and experiments have shown that the value of the factor *a* in formula (13) is approximately 2 because at the temperature used in the laboratory incineration of the fuel sample pyrite is decomposed to iron mono-sulphide and pure sulphur.

The second term $[2.5\beta_{S.A}(S_p^d+S_o^d)]$ expresses the increasing of the ash mass in the incineration process of fuel due to sulphating of oxides (for instance by formula (9)). The combustible sulphur conversion factor to sulphate $\beta_{S.A}$ depends on the amount of sandy-clay part in the oil shale and is expressed as $\beta_{S.A} = 0.034\,T^d$. In this formula *T* shows the apparent sandy-clay matter content in oil shale dry mass and is expressed by the formula:

$$T^d = A - 1.257\,(CO_2)_k^r,\ \%. \qquad (14)$$

During the laboratory incineration of oil shale approximately 50–80% of the combustible sulphur is bound with ash. A very high content of carbonates in the fuel enables partial binding of organic sulphur with ash also.

The third term $[(1-k_{CO_{2k}})(CO_2)_k^d]$ takes into account the thermal dissociation of carbonates in the laboratory incineration of the sample. The carbonates dissociation rate at the incineration of the Estonian oil shale $k_{CO_{2k}}$ = 0.99.

The difference between the laboratory ash content and the quantity of corrected ash $\Delta A^x = A^x - A_a^x$ (superscript "x" marks dry "d" or as received basis mass "r" of the fuel). For the Estonian oil shale:

$$\Delta A^x = (0.003T^d + 0.019)T^x + 0.01(CO_2)_k^x \text{, \%.} \quad (15)$$

The corrected proximate composition of the Estonian oil shale is:

$$\left.\begin{aligned}
&W_p^r = W^r + W_c^r = W^r + 0.022W^r\,;\\
&(CO_2)_{k.a}^r = (CO_2)_k^r\,;\\
&A_a^r = A^r - \Delta A^r = A^r - (0.0037\,T^d + 0.019)\,T^d - 0.01\,(CO_2)_k^r\,;\\
&P_a^r = R^r + S_p^r = P^r - (0.0037\,T^d - 0.003\,)\,T^r - 0.01\,(CO_2)_k^r\,.
\end{aligned}\right| \quad (16)$$

100%

The real proximate composition of oil shale:

$$\left.\begin{aligned}
&W^r = W^r;\\
&R^r = P^r + (0.0037\,T^d - 0.050)\,T^r + 0.01\,(CO_2)_k^r\,;\\
&M_c^r = A^r - (0.0037\,T^d - 0.05)\,T^r - 0.01\,(CO_2)_k^r\,;\\
&(CO_2)_k^r = (CO_2)_k^r\,.
\end{aligned}\right| \quad (17)$$

100%,

where M_c^r is the total content of mineral matter in oil shale dry mass without mineral carbon dioxide.

For the derivation of formulas (16) and (17) the content of crystalline water in oil shale was expressed as $W^x = 0.022\,T^x$, %, and the amount of marcasite sulphur as $S_p = 0.044\,T^x$, %.

On the basis of the results of the proximate analysis of oil shale and equation (6) the volume concentration of carbon dioxide is expressed by the following formula:

$$V_{CO_2} = 0.0145\,\varphi\; R^r + 0.00509\,k_{CO_2}\,(CO_2)_k^r = \quad (18)$$

$$= 0.0145\,\varphi\;[P^r + (0.0037\,T^d - 0.050\,)\,T^r + 0.01\,(CO_2)_k^r] + 0.0509k_{CO_2}\,(CO_2)_k^r\,, m^3 / kg\,.$$

5 Determination of carbon dioxide pressure in oil shale combustion products

Partial pressure of carbon dioxide in oil shale combustion products can be calculated by the following general formula:

$$p_{CO_2} = r_{CO_2}\ p, MPa, \qquad (19)$$

where

r_{CO_2} partial volume of carbon dioxide in oil shale combustion products;

p total pressure of oil shale combustion products, MPa.

Partial volume of carbon dioxide in oil shale combustion products is expressed as

$$r_{CO_2} = \frac{V_{CO_2}}{V_g},\ \text{m}^3/\text{m}^3, \qquad (20)$$

where

V_{CO_2} carbon dioxide volume concentration in normal conditions in oil shale combustion products per 1 kg fuel as received basis, m3/kg;

V_g total volume of oil shale combustion products per 1 kg fuel as received basis, m3/kg.

Total volume of oil shale combustion products per 1 kg fuel as received basis is expressed as the sum:

$$V_g = V_{CO_2} + V_{SO_2} + V_{N_2} + V_{O_2} + V_{H_2O},\ \text{kg/m}^3, \qquad (21)$$

where

$V_{SO_2}, V_{N_2}, V_{O_2}, V_{H_2O}$ respectively sulphur dioxide, nitrogen, oxygen and water vapour volume concentration in normal conditions in oil shale combustion products per 1 kg of fuel as received basis, m3/kg.

Sulphur dioxide volume concentration:

$$V_{SO_2} = 0.007(1 - k_S)(0.0176\ R^r + S_p^r),\ \text{m}^3/\text{kg}. \qquad (22)$$

Nitrogen concentration:

$$V_{N_2} = 0.79\ \lambda\ V^0 + 0.0026\ R^r,\ \text{m}^3/\text{kg}. \qquad (23)$$

Oxygen concentration:

$$V_{O_2} = 0.21(\lambda - 1), \quad m^3/kg. \tag{24}$$

Water vapour concentration:

$$V_{H_2O} = 0.0108\, R^r + 0.0124\, W^r + 0.0161\, \lambda\, V_0^r, \; m^3/kg. \tag{25}$$

The stoichiometric amount of air for oil shale burning:

$$V_0^r = 0.918\, R^r + 0.033\, S_p^r, \; m^3/kg; \tag{26}$$

where

ks combustible sulphur binding factor with ash;

S_p^r pyrite (marcasite) sulphur content in oil shale as received basis, %;

Rr content of organic matter in oil shale as received basis (formula (17)), %;

λ air/fuel ratio.

6 Determination of oil shale composition depending on the heating value

According to (Ots, 1977) the heating value of the Estonian oil shale dry mass can be expressed as a function of ash and mineral carbon dioxide content. In practice we often have to determine the composition of oil shale depending on the heating value of fuel.

The basic formula for analytical determination of LHV of dry mass of oil shale depending on ash and carbon dioxide content is as follows:

$$Q_l^d = 8.223 - 0.0722\, A^d - 0.1043\, (CO_2)_k^d, \; MJ/kg. \tag{27}$$

On the basis of analysis of oil shale samples and formula (27) the following statistical functions $A^d = F_1(Q_l^d)$, $(CO_2)_k^d = F_2(Q_l^d)$ and $W^r = F_3(Q_l^d)$ were established (Mäeküla and Ots, 1977).

$$A^d = 52.9 + 0.68\, Q_l^d - 0.087\, (Q_l^d)^2, \; \%; \tag{28}$$

$$(CO)_k^d = 42.6 - 2.79\, Q_l^d + 0.061 (Q_l^d)^2, \; \%; \tag{29}$$

$$W^r = -9.8 + 3.41\, Q_l^d - 0.136\, (Q_l^d)^2, \; \%. \tag{30}$$

7 Calcium oxide behaviour in oil shale combustion

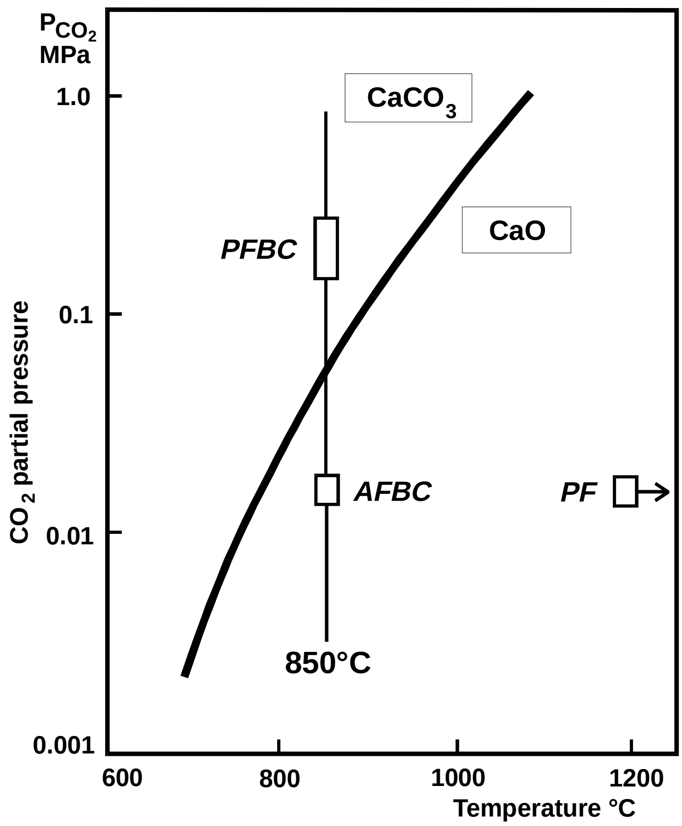
7.1 General

Calcium oxide is one of the most important mineral components of oil shale and its behaviour in the combustion process is of great importance in carbon dioxide emission. The behaviour of the minerals of carbonates depends on temperature and carbon dioxide pressure in the combustion products.

The carbon dioxide equilibrium pressure, depending on temperature, is expressed by the reaction $caca_o \Leftrightarrow CaO + CO_2$ and is illustrated in Figure 19.

The Thermal Engineering Department of Tallinn Technical University has laboratory equipment for investigating processes in the mineral matter of fuels depending on temperature, pressure, composition of ambient environment and gas velocity. The equipment is envisaged for operation pressures up to 1.5 MPa and temperature up to 980°C. The gaseous environment contains N_2, O_2, CO_2 and SO_2.

Figure 19 $CaCO_3$ dissociation equilibrium diagram



This experimental equipment was used for the investigation of thermal decomposition of limestone. The goal of the experiments with limestone was to confirm the influence of carbon dioxide pressure on the characteristics of calcium carbonate decomposition. The tested limestone contained 95 mass % of $CaCO_3$. Its chemical composition was the following CaO -- 53.2%; MgO – 1.8%; SO_3 – 0.4%; R_2O_3 – 1.1%; heating losses at 1000°C – 41.7%. The research was carried out at atmospheric as well as at pressurised conditions at 850°C in the following gaseous atmosphere (vol. %): 86.1% N_2, 10.2% CO_2 and 3.7% O_2.

The results of the experiments in atmospheric and pressurised conditions with limestone decomposition rate changing in time are given in Figure 20. The decomposition rate of limestone was calculated on the basis of limestone mass decrease at heating by the following formula:

$$k_{CO_2} = 1 - \frac{(CO''_{2k} / A'')}{(CO'_{2k} / A')}, \qquad (31)$$

where

CO2k″ mineral CO2 content in the heated residue, %;

CO2k′ mineral CO2 content in initial material, %;

A″ heated residue (ash content) of the heated sample (limestone), %;

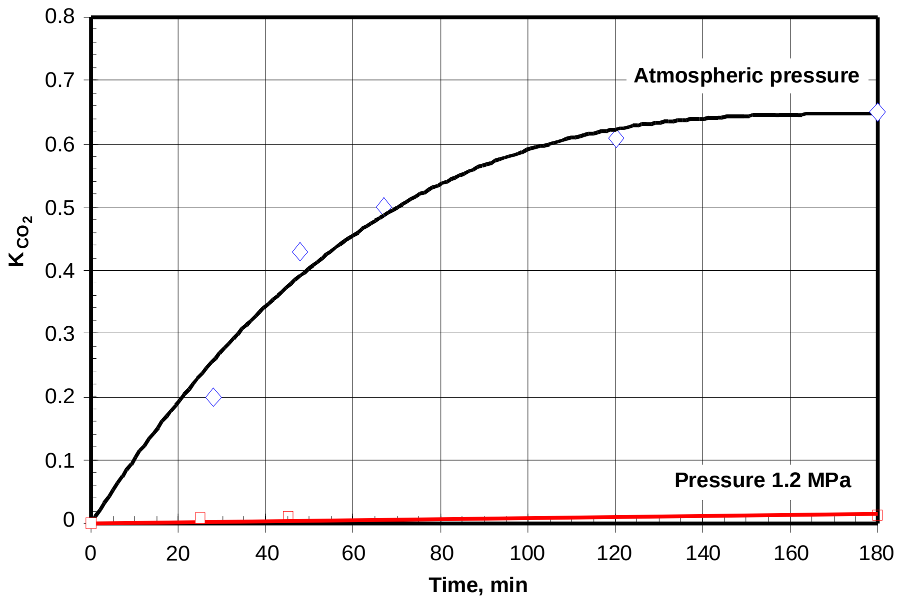
A′ heated residue (ash content), %.

The experiments with limestone showed that in pressurised conditions (CO_2 concentration in gas medium was 10.2 vol. %) no change of mass occurred and the decomposition rate of carbonates was 0.01. The limestone decomposition rate above 0 (actually 0.01) suggests that limestone contains besides $CaCO_3$ also a small amount of other minerals.

However, at atmospheric pressure and the same carbonate dioxide volume concentration in gaseous environment a remarkable decrease of limestone mass depending on time was observed.

Consequently the presented results confirm a big difference in the behaviour of limestone, an important component of oil shale, in pressurised and atmospheric combustion.

Figure 20 Decomposition rate of carbonates in a limestone sample as a function of time at 850°C



7.2 Calcium carbonate behaviour at combustion in atmospheric conditions

When the Estonian oil shale is burnt in atmospheric conditions the CO_2 pressure in flue gas is in the range of 0.014–0.016 MPa and the combustion temperature in AFBC is 800–900°C. In PF combustor the maximum temperature usually exceeds 1400°C. These points in Figure 19 are located below the equilibrium curve and thermal dissociation of calcite is thermodynamically possible t.

The experimental results of investigation on oil shale combustion in atmospheric pressure show that independently from burning technology (PF, AFBC, etc.) the dissociation process of the carbonates occurs in very high ratio.

Carbon dioxide separated from carbonates goes into the flue gas. Dissociation of calcite (also dolomite) is the main source of calcium oxide at firing oil shale in atmospheric combustion conditions. Calcium oxide is one of the most active components of the ash formed from the oil shale carbonates.

Part of the calcium oxide originating from the carbonate stays in free form and the remaining part reacts to some extent with sandy-clay minerals and transforms into clinker minerals. Bi-calcium silicate $2CaO{\cdot}SiO_2$ (belite) is formed in reaction with quartz oxide. The formation of tri-calcium bi-silicate $3CaO{\cdot}2SiO_2$ is also possible simultaneously with belite formation. Some part of calcium oxide will react with aluminium and iron oxides.

Dissociation of calcite and dolomite is the main source of calcium oxide in the process of firing oil shale. Part of the calcium oxide originating from carbonates transforms into clinker minerals (e.g., β-$2CaO{\cdot}SiO_2$). Calcium oxide balance in firing fuels like the Estonian oil-shale may be divided into three parts as follows (Ots, 1977):

(i) CaO combined with carbonates, CaO_c;

(ii) CaO combined with clinker minerals, CaO_b, and

(iii) CaO in free form, CaO_f..

Marking $K_c = CaO_c/CaO$; $Kb = CaO_b/CaO$; $K_f = CaO_f/CaO$, where the total calcium oxide percentage in ash $CaO = CaO_c + CaO_b + CaO_f$. Obviously, $K_c + K_b + K_f = l$.

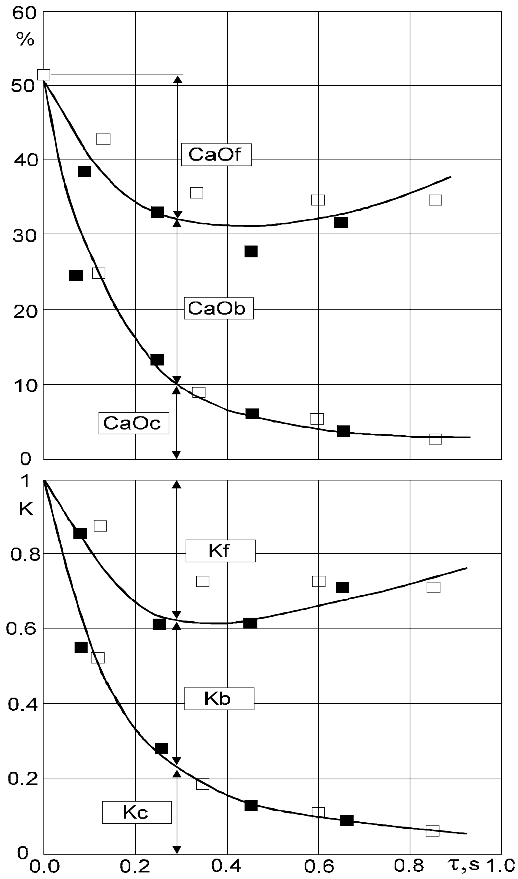
The balance of calcium oxide versus time in the flame of the Estonian pulverised oil shale is shown in Figure 21. One can see that the amount of combined CaO in carbonates is reduced continuously (thermal dissociation of carbonates takes place), but binding with clinker minerals continues to increase. The content of free calcium oxide in ash increases at first and then decreases slowly. The ratio of free CaO to the total CaO content in the fly ash after combustion remains in the range 25–30%.

SO_2 capturing with ash in atmospheric combustion takes place via CaO according to reactions (8) and (9).

7.3 Calcium carbonate behaviour at combustion in pressurised conditions

At oil shale combustion in pressurised conditions the total pressure in the combustor is 1.2–1.5 MPa. If oil shale is burnt in PFBC, the combustion temperature of the fuel will be in the same range as at AFBC (800–950°C), but the CO_2 pressure in the combustion products, depending on the total pressure, will be in the range 0.14–0.16 MPa. It must be mentioned that the partial pressure of carbon dioxide in the combustion products does not depend only on the composition of the organic part of the fuel and its

Figure 21 Calcium oxide conversion along the length of the pulverised Estonian oil shale flame. Maximum temperature in the flame is 1450–1500°C



moisture content, but also to some extent on the decomposition rate of carbonates (carbonates behaviour). According to Figure 19 and Figure 20 thermal dissociation of calcite is not possible by burning oil shale in PFBC.

Experimental investigations (Külaots et al., 1997, Ots et al., 1997) have shown that despite of the impossibility of calcite dissociation in gas ambience in which CO_2 pressure is higher than the equilibrium pressure for thermal dissociation of $CaCO_3$, some decomposition of carbonates occurs due to reactions between CaO present in carbonates, sulphur dioxide and ash components. Consequently, the mechanism of carbonates decomposition in pressurised combustion is different from that at the combustion of the fuel in atmospheric conditions.

Experiments (Külaots et al., 1997; Iisa, 1992) show that in case the partial pressure of carbon dioxide in combustion products exceeds the equilibrium pressure of CO_2, sulphur dioxide will react directly with calcium carbonate as indicated by the following general reactions.

Limestone

$$2CaCO_3 + 2SO_2 + O_2 \Rightarrow 2CaSO_4 + 2CO_2\,. \qquad (32)$$

Dolomite

$$2CaMg(CO_2)_3 + 2SO_2 + O_2 \Rightarrow 2CaSO_4 \cdot MgO + 4CO_2 \qquad (33)$$

Experimental investigations (Külaots et al., 1997) show that in PFBC combustion situations full desulphurisation of Estonian oil shale combustion products is possible. The decomposition rate of carbonates due to the sulphation of CaO according to reaction (32) depends on Ca (in carbonates)/S molar ratio. Proceeding from the content of combustible sulphur in oil shale the decomposition rate of carbonates due to reaction (32) is in the range 0.08–0.10 (Ots et al., 1997).

The actual decomposition rate of carbonates is higher than the $CaCO_3$ decomposition rate established on the basis of sulphation reaction (32) proceeding from the sulphur content in oil shale. Consequently, direct chemical reactions between the carbonates and the sandy-clay minerals of oil shale must take place. The following reactions are possible:

$$2CaCO_3+SiO_2 \rightarrow 2CaO{\cdot}SiO2+2CO_2, \quad (34)$$

$$CaCO_3+Al_2O_3 \rightarrow CaO{\cdot}Al_2O_3+CO_2, \quad (35)$$

$$CaCO_3+Fe_2O_3 \rightarrow CaO{\cdot}Fe_2O_3+CO_2. \quad (36)$$

Considering the experimentally established decomposition rates of carbonates, it is obvious that reactions (34)–(35) play a significant role in carbonate decomposition processes at the burning of oil shale in PFBC conditions.

7.4 Oil shale heating value at combustion in pressurised conditions

The starting point for the determination of the higher or lower heating values of solid fuels (HHV or LHV) is calorific value established experimentally in laboratory. In most cases it is the calorific value in the calorimetric bomb. The calorific value of the fuel established in the calorimetric bomb or by some other experimental method does not correspond to heat release in a real combustor because the fuel combustion in a calorimetric bomb differs from combustion in real conditions.

In the burning process not only the oxidising of organic components of the fuel but also conversion processes take place in the inorganic matter. The conversion processes in the inorganic matter of fuel and its heat effects influence the heating value remarkably. Those thermal effects depend first of all on the qualitative and quantitative composition of the inorganic part of the fuel and secondly on the parameters of the combustion process such as temperature, composition of ambient gas and pressure. In the burning of fuels with a high content of carbonates the processes connected with their decomposition affect greatly the heating value.

The heating value of a fuel is the sum of the heat release at the burning of its organic part and the thermal effects of minerals in inorganic matter at defined conditions (compromise conditions).

The problem of the heating value of fuel is very complicated, especially for oil shale, due to the intricate composition of inorganic matter. The processes taking place in inorganic matter of oil shale have a remarkable influence on the absolute heating value of the fuel.

However, a detailed discussion of the problem of the heating value of oil shale is not the aim of the present study. Below only the most important conclusions linked with the decomposition of carbonates in oil shale combustion are presented.

As mentioned above, not only the oxidising reactions of the organic components of the fuel (combustion process) but also the heat effects in the inorganic matter affect the heating value. The most important heat effects that influence the heating value of oil shale are the following:

- The endothermic heat effects from the decomposition of carbonates.
- The exothermic heat effects from the formation of calcium sulphate.
- The endothermic heat effects from the formation of double calcium oxide minerals.

Taking into account these additional heat effects, the heating value of oil shale is expressed by the formula:

$$Q_L^r = \left[Q_L^r\right] + \Delta\left(Q_L^r\right)_K + \Delta\left(Q_L^r\right)_T = \left[Q_L^r\right] + \Delta Q_L^r, \quad (37)$$

where

$\left[Q_L^r\right]$ the LHV as received basis by the full decomposition of carbonates, taking into account full conversion of the combustible sulphur to sulphates and that the rest of calcium oxide of carbonates stays in free form;

$\Delta\left(Q_L^r\right)_K$ the heat effect of incomplete decomposition of carbonates;

$\Delta\left(Q_L^r\right)_T$ the heat effect from reactions between CaO and sandy-clay minerals (formation of double calcium oxide minerals).

In the course of combustion under pressurised conditions the combustible sulphur is fully converted to calcium sulphate and it is taken into account in the term $\left[Q_L^r\right]$.

The heat effect of incomplete decomposition of carbonates depends on the quantity of mineral CO_2 in oil shale and on the decomposition rate of carbonates. It can be expressed by the formula:

$$\Delta\left(Q_L^r\right)_K = 0{,}0406\,\left(1 - k_{CO_2}\right)\left(CO_2\right)_k^r, \text{ MJ/kg}, \quad (38)$$

where

$\left(CO_2\right)_k^r$ the content of mineral carbon dioxide in oil shale as received basis, %;

k_{CO_2} the decomposition rate of carbonates.

The heat effect from reactions between CaO and sandy-clay minerals is expressed by the formula:

$$\Delta\left(Q_L^r\right)_T = 0{,}0158\,\left(k_{CO_2} - 0{,}10\right)\left(CO_2\right)_k^r, \text{ MJ/kg}. \quad (39)$$

The heating value of oil shale depends strongly on the behaviour of carbonates in the combustion processes. This reflects different values of decomposition rates depending on the combustion technology of the fuel (PF, AFBC, PFBC).

The heat release in oil shale pressurised combustion is remarkably higher due to the lower decomposition rates of carbonates compared to atmospheric burning, i.e. the heating value of oil shale is increased in pressurised combustion.

Treating oil shale as a system consisting of four parts (W^r, A^r, T^r and $(CO_2)_k^r$) it is possible to establish the above-mentioned oil shale components on the basis of the statistical data as a function of heating value. Following these and observing the quantity of carbon dioxide as a function of oil shale LHV as received basis, Figure 22 shows the dependence of oil shale LHV increasing factor on the decomposition rate of carbonates and LHV as received basis. The LHV increasing factor of oil shale is expressed by the formula:

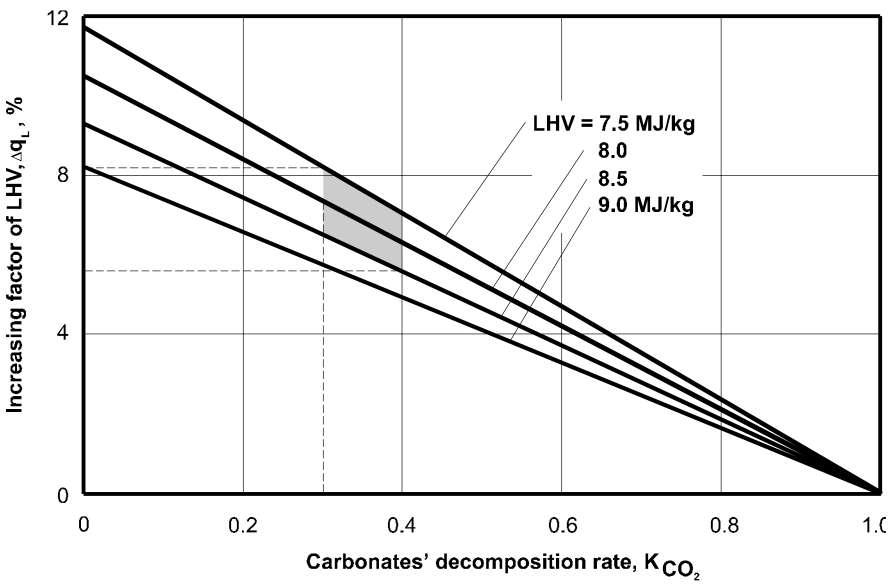
$$\Delta q_L = \Delta Q_L^r / \left(Q_L^r\right)_{k_{CO_2}=1}, \ \%. \quad (40)$$

The factor Δq_L indicates the increasing of LHV as a result of incomplete decomposition of carbonates compared to LHV in case of full decomposition of carbonates.

The shaded area in Figure 22 shows a probable area of the decomposition rate of carbonates in pressurised conditions of combustion. Burning the Estonian oil shale in pressurised conditions with net LHV 7.5–8.5 MJ/kg the heating value of oil shale increases 5.5–8.0% compared to combustion at atmospheric pressure.

As mentioned above, the main heat effect connected with processes in the burning of mineral matter of oil shale is decomposition of carbonates. When burning oil shale in atmospheric conditions the decomposition rate of carbonates is 0.97–0.98. In pressurised conditions the decomposition rate of carbonates is in the range 0.3–0.4 (experimental data). According to these data the burning of oil shale in pressurised conditions gives possibilities to "save" about 60–70% of heat due to incomplete decomposition of carbonates.

Figure 22 Dependence of increasing factor of the LHV Δq_L of oil shale on the decomposition rate of carbonates



7.5 Decreasing the carbonate dioxide concentration in flue gas by burning oil shale in pressurised conditions

The decomposition rate of carbonates in the combustion process of oil shale also affects the CO_2 concentration in the combustion products. The amount of CO_2 in the flue gas depends on the content of organic and mineral carbon in the fuel. Its amount at burning the Estonian oil shale can be calculated by formula (18).

The decreasing factor of the carbonate dioxide concentration in flue gas can be expressed by the following formula:

$$\Delta v_{CO_2} = 100\left\{1 - \left[\left(V_{CO_2}\right)_{k_{CO_2}}\right] / \left(V_{CO_2}\right)_{k_{CO_2}=1}\right\}, \%, \tag{41}$$

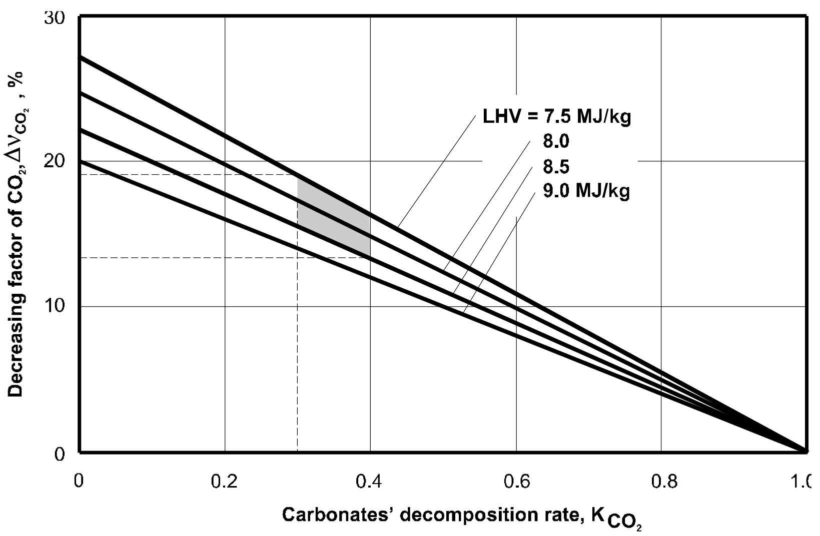
where

$\left(V_{CO_2}\right)_{k_{CO_2}=1}$ maximum content of carbonate dioxide in the combustion products; ($k_{CO_2} = 1$), m3/kg;

$\left(V_{CO_2}\right)_{k_{CO_2}}$ carbonate dioxide content in the flue gas at carbonates decomposition rate k_{CO_2}, m3/kg.

The calculated values of the decreasing factor of carbonate dioxide concentration in flue gas depending on the decomposition rate of carbonates in the Estonian oil shale of LHV as received basis are in the range 7.5–9.0 MJ/kg are given in Figure 23. These calculations were made on the basis of the composition of the organic part of the Estonian oil shale presented in Table 21.

Figure 23 Decreasing factor of carbonate dioxide concentration Δv_{CO_2} in the combustion products depending on decomposition rate of carbonates



We can see that when burning oil shale with net LHV = 8.5 MJ/kg the concentration of carbon dioxide in flue gas may theoretically decrease by 23% if the carbonates do not decompose.

The shaded area in Figure 23 shows the probable decomposition rates of carbonates at combustion in pressurised conditions. By burning the Estonian oil shale with net LHV 7.5–8.5 MJ/kg in pressurised conditions the CO_2 concentration in flue gas can be reduced approximately by 13-20% compared to atmospheric combustion.

8 Technologies of burning the Estonian oil shale and their influence on carbon dioxide emission

8.1 Pulverised firing technology

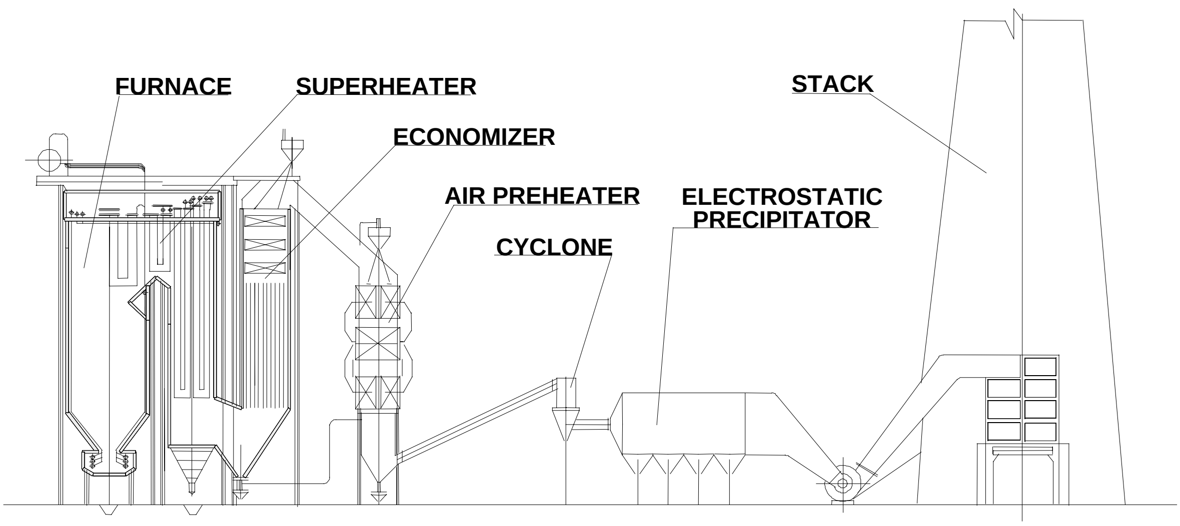
Today pulverised firing (PF) technology is used in oil shale fired power plants in Estonia. The first PF oil shale boilers were modernised coal boilers with 14–18 kg/s steam output and steam parameters 3.5–4 MPa and 420–450°C in Kohtla-Järve and Ahtme power plants.

The designed capacity of the Baltic Power Plant was 1624 MW_e (now its real capacity is 1390 MW_e). There are eight condensing turbines, each of 100 MW_e capacity, and two back pressure turbines both of 12 MW_e capacity, receiving steam from 18 boilers (TP-17 type boilers) with nominal 61 kg/s steam output and steam parameters 9.8 MPa and 515°C. The TP-17 type boilers were put into operation between 1959 and 1962. Each of the four 200 MW_e power units has two boilers (TP-67 type boilers) of 89 kg/s steam output and parameters of superheated/reheated steam 13.8/2.2 MPa and 515/525°C. The boilers of TP-67 type were put into operation between 1963 and 1973. In the older part of the Baltic Power Plant boilers of TP-17 type were in operation just about 230 thousand hours and TP-67 type boilers 175 thousand hours.

In 1973 the Estonian Power Plant was run at a capacity of 1610 MW_e. Seven turbines of 200 MW_e capacity and one of 210 MW_e as well as boilers (TP-101 type boilers) of 89 kg/s steam output at 13.8/2.2 MPa pressure and 520/525°C were installed.

The typical layout of gas ducts with an ash separation system in an oil shale boiler is presented in Figure 24.

Figure 24 Flue gas ducts of a PF boiler fired with Estonian oil shale



The boilers used at the Baltic and Estonian power plants had been specially designed for burning Estonian oil shale. The design principles for those boilers were worked out in the Thermal Engineering Department of Tallinn Technical University. The design of a PF boiler fired with oil shale differs in principle from the design of PF coal boilers.

Before burning, the lump oil shale is crushed and after that pulverised in hammer mills. Mills are equipped with dust separators of various types. All oil shale PF boilers use direct-fired systems where pulverised fuel is transported directly from the milling system to burners by the air. Direct-fired systems of oil shale boilers are balanced-draft furnaces.

The TP-17 boilers of 100 MW_e power units use the corner-fired system. The fuel and air are admitted from the furnace corner in vertical layers. Both pulverised oil shale and air are projected from the corner directly through the burners of the furnace along a line tangent to a small horizontal plane circle in the centre of the furnace.

The horizontal front-fired system is used in the PF oil shale boilers of the 200 MW_e power units. In the horizontal-fired system the pulverised oil shale is mixed with combustion air in individual burners of turbulent type. The burners are located in rows on the front wall only.

As mentioned above the Estonian oil shale is characterised as a fuel with a high content of volatile matter. The devolatilisation of the organic matter of oil shale and intensive output of volatiles will begin already at low temperatures (300–400°C), providing highly stabile combustion of pulverised fuel.

Activation energy E=38.8 kJ/kmol and the pre-exponential factor k_0=609 1/s describe the combustion intensity of oil shale volatile matter depending on temperature. The combustion intensity of the volatile matter of oil shale is determined first of all by oxygen concentration. Approximately 80–90% of the potential heat of oil shale is realised in the combustion zone of volatile matter.

The char of the Estonian oil shale is a porous material with a coefficient of inner oxygen diffusion D_0=0.049 cm^2/s at temperature T_0=273 K. Oil shale char contains a certain amount of hydrogen. The carbon/hydrogen ratio is approximately 25. The combustion kinetic constants of char are the following: $S_i k_0$=1.857×1010 $cm^3/(g \cdot s)$ and E=100 kJ/kmol.

The total combustion time of pulverised oil shale is in the range 1–1.5 s in normal burning conditions (excess air ratio 1.2, maximum temperature of flame 1400–1500°C).

The amount of unburned carbon and mineral carbon dioxide in oil shale burning residues for PF boilers depends mainly on the flame temperature, residence time of particles in the combustion zone, fineness of pulverised fuel and oxygen concentration but also on the aerodynamic design of the furnace. Thanks to the very high content of volatile matter in the organic part and also high reactivity of char the efficiency of the combustion of pulverised oil shale is very high.

The content of organic carbon in fly ash after the boiler is in the range 0.01–0.15%, depending on the boiler type, dust characteristics and burning conditions . The content of organic carbon in the bottom ash is 0.1–0.4%. The efficiency of carbon conversion to carbon dioxide φ (formula 6) is very high with an average value of 0.997.

The content of mineral carbon dioxide in fly ash after the boilers is 1.0–1.5% and in the bottom ash 3–6%. The decomposition rate of the mineral part of carbonates is in the range 0.96–0.99 (average value 0.98), depending on the type of boiler, dust characteristics and burning conditions.

The proximate annual average composition of oil shale as received basis, utilised in the Baltic Power Plant, was in 1996 as follows:

Q_l^r = 8.3 MJ/kg	W^r = 11.2%	A^r = 45.7%	$(CO_2)_k^r$ = 17.5%

and in the Estonian Power Plant

Q_l^r = 8.4 MJ/kg	W^r = 11.2%	A^r = 46.1%	$(CO_2)_k^r$ = 18.3%.

Proceeding from the presented composition of oil shale, net efficiency of power plants, carbon conversion efficiency to carbon dioxide and decomposition rate of carbonates the Baltic Power Plant is characterised by the following data:

b = 1.48 kg/kW·h	q = 12.87 MJ/kW·h	$\rho_{CO_2} V_{CO_2}$ = 0.90 kg/kg	m_{CO_2} = 1.39 kg/kW·h

For the Estonian Power Plant these values are:

b = 1.48 kg/kW·h	q = 12.43 MJ/kW·h	$\rho_{CO_2} V_{CO_2}$ = 0.91 kg/kg	m_{CO_2} = 1.35 kg/kW·h

The conventional PF technique for burning oil shale is characterised by very intensive fouling of the heat transfer surfaces of the boilers with bound sulphate ash deposits and high temperature corrosion. Corrosion is caused first of all by chlorine, which is bound in the combustion process with potassium, volatilised from oil shale sandy-clay minerals in the high temperature environment as a result of their thermal decomposition and forming corrosively very active KCl.

Oil shale power plants have comparatively high emission of sulphur dioxide in spite of the high binding capacity of sulphur dioxide by ash in the gas passes of the boilers. Approximately 15–20% of the total sulphur in oil shale goes into stack as SO_2.

Older TP-17 boilers of the Baltic Power Plant have operated at lower than designed steam temperature. The average operation efficiency of boilers is in the range 82–83%.

Two 100 MW_e turbines in the Baltic Power Plant were reconstructed to the controlled extraction turbines. The average pressure of the extraction steam is 0.23 MPa.

The TP-67 boilers of the Baltic Power Plant and the TP-101 boilers of the Estonian Power Plant were designed for steam temperatures 540°C. Because of very intensive corrosion of tubes of the superheater heat transfer surfaces the steam temperature was reduced to 515/525°C for TP-67 boilers and to 525/524°C for TP-101 boilers. The average operation efficiency of TP-67 and TP-101 boilers is 82–83%.

To raise the initial steam temperatures new boiler alloys for superheaters with higher corrosion resistance are required. The change of the material of superheaters is an economic question – will the cost of new alloys and replacement work be compensated for by the increased economy due to higher steam temperature?

The net average efficiency of oil shale power plants is 28–29%. The comparatively low efficiency of plants is due to low efficiency of the steam cycle where the superheated steam temperature has a great role. Another reason is the low efficiency of boilers. Raising the superheated and reheated steam average temperature to 530/535°C would increase the steam cycle efficiency by about 0.8%. Reconstruction of the low-pressure stage of the turbine would increase the efficiency of the low-pressure stage by 1.5-2%. Reconstruction of the boilers would raise the boiler efficiency up to 85–86%. Application of the above-mentioned measures and a 2% reduction of the auxiliary power would enable to increase the efficiency of the power units of the existing power plants by up to 30.5–31.5% as maximum.

Estimated investments necessary for the realisation of the above-described applications are about 1500–2000 EEK/kW·h.

If the net efficiency of the Estonian Power Plant is raised to 31.5% and proceeding from the composition of oil shale received, the plant will be characterised by the following parameters:

b = 1.36 kg/kW·h	q = 11.42 MJ/kW·h	m_{CO_2} = 1.24 kg/kW·h

Sulphur dioxide emission can be radically reduced using PF technology with gas-cleaning equipment. Using the gas-cleaning equipment of cleaning efficiency 85–90% it is possible to reduce sulphur dioxide concentration in the combustion products to 150-200 mg/m^3 (in normal cubic meter of gas at oxygen concentration 6%). The investments necessary for the gas-cleaning equipment, depending on type, are within the range 1400–2250 EEK/kW. The use of gas-cleaning equipment decreases to some extent the power plant efficiency, because the need for auxiliary power increases.

8.2 Atmospheric circulating fluidised bed combustion technology

Fluidised bed combustion (FBC) is a widespread technique nowadays. A bed of inert particles, such as sand, stone and ash, can be made to exhibit many of the properties of a fluid – fluidised - by passing a gas medium upwards through the bed at a velocity sufficiently high for frictional drag to support the weight of the particles, but not so high as to initiate pneumatic transport of the particles (Circulating Fluidised Beds, 1997; Pressurised Fluidised Bed Combustion, 1995). The fluidised bed regime thus exists between the packed bed and the pneumatic transport states. If such an air-fluidised bed of inert particles heated to a temperature higher than ignition temperature is introduced into the fuel, the fuel burns without it being necessary to have a high temperature. In practice the bed temperature is between 800 and 950°C. The oxidising ambience with low temperature in the combustor reduces the risk of slagging and fouling the heat transfer surfaces. The combustion regimes should avoid the sintering of ash and bed material.

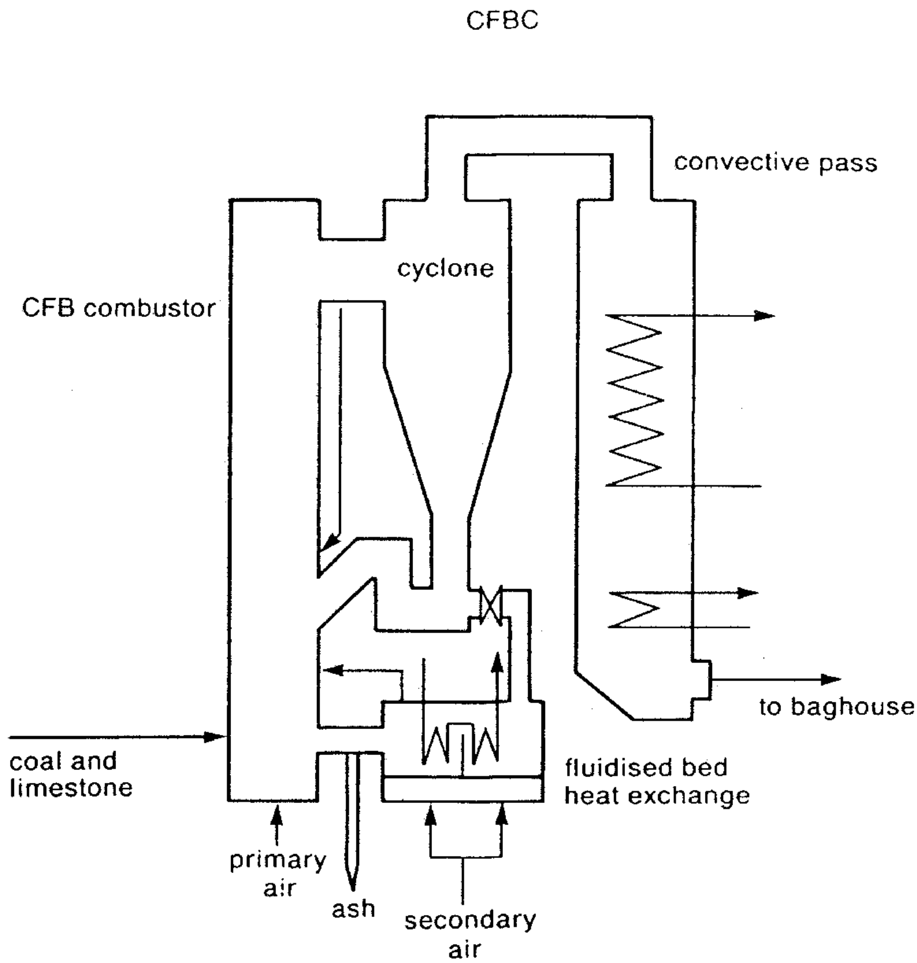
FBC is usually classified as either bubbling (BFBC) or circulating fluidised bed (CFBC) combustors. In BFBC the air velocity is low (1–3 m/s) and the particles behave like a boiling fluid and stay in the bed. To achieve the above-mentioned bed temperature, usually used in BFCB, heat exchange tubes are immersed within the bed particles.

In CFBC the air velocity is higher (6–10 m/s) and much material leaves the bed and is collected by cyclone separators. In all CFB recirculation systems a standpipe is required to allow the solid materials to flow from the low-pressure region of the bed outlet to a higher-pressure region in the bottom. Due to very low fuel concentration in the combustor and the high thermal capacity of solids there is no need for tubes of heat transfer surfaces in the bed. Tubes of water walls cool the upper part of the combustor. In modern CFBC boilers the fluidised bed heat exchanger (FBHE) is used. Solid particles separated from the cyclone are introduced to the external FBHE through a plug valve. The FBHE is a bubbling bed heat exchanger fluidising by air. The heat transfer surfaces in FBHE could be water economiser, steam generating or steam superheater tubes. Ash from the FBHE is returned into the combustor or into the ash cooler. A scheme of the CFBC boiler is given in Figure 25.

The fluidised combustion technique for the Estonian oil shale is not in commercial use. We have some experience with the Estonian oil shale in test facilities. The tests with oil shale were carried out in 1 MW_{th} CFBC test facilities of Hans Ahlstrom Laboratory in Karhula, Finland, and LLB Lurgi in Frankfurt am Main, Germany (Arro et al., 1997a, 1997b), and also in 0.15 MW_{th} test facility in the University of British Columbia in Vancouver, Canada.

One peculiarity of the CFB burning cycle is very intensive pulverising of oil shale ash. As a result the part of very fine fly ash rises significantly compared to PF of oil shale. Up to 40–60% of the total ash was collected as fines. Such fine grain composition of fly ash is the result of intensive pulverising of ash particles in the CFBC. Free CaO and MgO formed in decomposition of carbonates are soft and easily ground. The median size of fly ash was 13–26 μm.

Figure 25 Atmospheric circulating fluidised bed boiler



Tests of different CFBC devices show that sulphur dioxide is fully bound with ash and the SO_2 binding factor with ash is approximately 1. Consequently, using the atmospheric CFB (ACFB) technology all the sulphur in oil shale will be captured with ash and the use of gas-cleaning equipment is not necessary, neither is additional sorbent for sulphur dioxide capturing needed due to the original qualities of oil shale.

The corrosive activity of the Estonian oil shale ash is mainly caused by chlorides (KCl, $CaCl_2$). The chlorine content in CBFC ash depends strongly on the median grain size of particles (Arro et al., 1997a). The maximum chlorine content occurs in fly ash from the filter (0.6–1.0%). The circulating ash is significantly coarser compared to fly ash (0.04–0.18%) and has also lower high temperature corrosion activity. This allows to locate the high temperature sections of the superheater and the reheater into FBHE and to raise the steam temperature before the turbine. Obviously this enables to increase the temperature of superheated steam up to 540/540°C and to raise the efficiency of the steam cycle. When the ACFB oil shale combustion technology is applied the boiler efficiency is within the range 87–89%. Proceeding from the 200 MW_e electrical power of the power-generating unit, 540/540°C temperature of superheated/reheated steam, the primary steam pressure 14 MPa and the boiler efficiency 87-89%, it is possible to increase the power unit efficiency of the oil shale power plant up to 33-34%, using the ACFB technique.

The investments needed for replacing the PF oil shale boilers with the ACFB technique, taking into account the 200 MW_e unit capacity, are of the order of magnitude 6000–7000 EEK/kW.

The decomposition rate of carbonate minerals at burning oil shale in ACFBC is in the range 0.88–0.92. Proceeding from the following composition of the oil shale

Q_l^r =8.4 MJ/kg	W^r = 11.2%	A^r = 46.1%	$(CO_2)_k^r$ = 18.3%

the power plant with ACFB combustion technique (η = 0.33, φ = 1, k_{CO_2} = 0.9) is characterised by the following parameters:

b = 1.30 kg/kW·h	q = 10.92 MJ/kW·h	$\rho_{CO_2} V_{CO_2}$ = 0.89 kg/kg	m_{CO_2} = 1.16 kg/kW·h

Consequently, the specific emission of carbon dioxide will fall by 14--16% when the ACFBC technique of burning oil shale is used instead of the PF combustion techniques.

8.3 Pressurised fluidised bed combustion technology

Using the pressurised fluidised bed (PFB) combined-cycle technology it is possible to increase the net efficiency of thermal power engine (power plant) compared to the conventional power plant operating on the atmospheric pressure combustion technique. The combined gas-steam cycle provides that effect. The system includes two heat power engines (machines) – gas turbine unit (Brayton's cycle) and steam engine (Rankine's cycle). In such a combined energy conversion system the gas turbine operates in an open cycle, but the steam side in a closed cycle. The useful adiabatic enthalpy drop from the gas turbine obtained from the pressurised combustion is added to the adiabatic enthalpy drop from the steam cycle at this combination. From the power output of the pressurised combustion heat power engine about 20-25% falls to the gas turbine cycle and the remaining 80-75% to the steam turbine cycle, depending on the thermal parameters of the heat power engine.

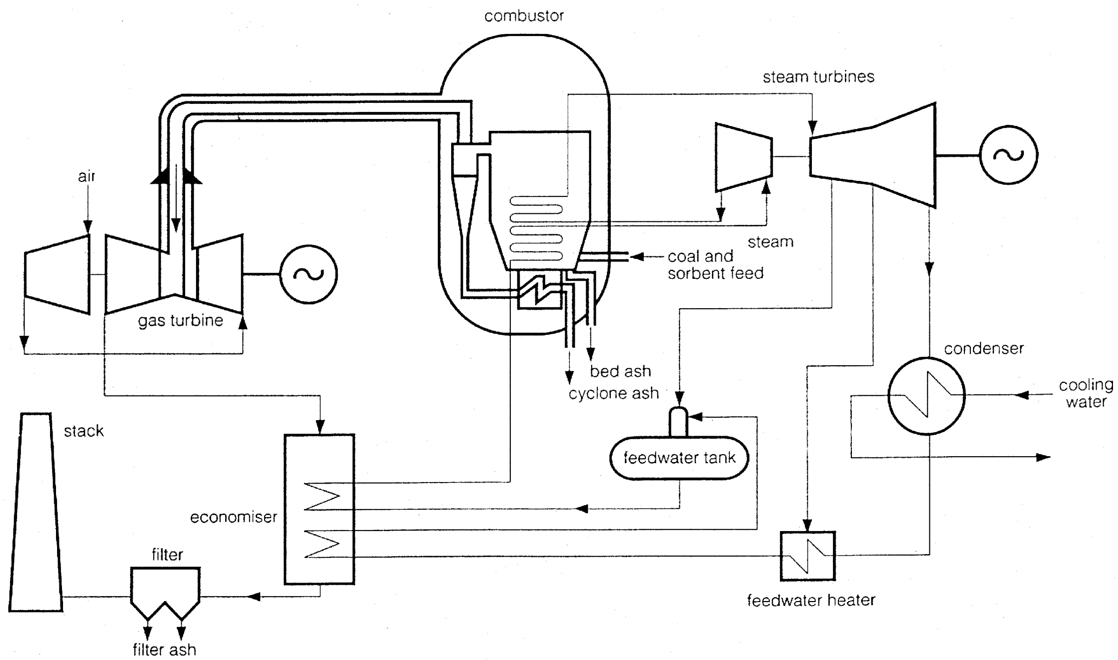
From the standpoint of the boiler construction the pressurised combustion thermal power engines are divided into bubbling bed and circulating bed units.

Figure 26 presents a scheme of a simplified thermal power engine that uses bubbling bed PFBC technology.

The gas turbine compressor supplies air to a pressurised vessel which contains a bubbling fluidised bed. Tubes of heat transfer surfaces are immersed within the fluidised bed of the fuel for generating and superheating the steam from water. Fuel and sulphur sorbent are fed into the fluidised bed combustor. In burning the Estonian oil shale, which itself contains a sufficient amount of limestone, no additional sorbent is needed. This simplifies the system as a whole.

The fuel is fed into the fluidised bed either as a dry suspension in air or as a water-mixed paste using pumps. Generally dry fuel feeding is used when the heating value of the fuel is low and its sulphur content is high. The fuel fed into the bed is previously mixed with a sulphur sorbent, either limestone or dolomite. The particle size of both the fuel and the sulphur sorbent is usually >5 mm.

Figure 26 Scheme of a bubbling PFBC heat power engine



The combustion of the fuel and also partial absorption of sulphur takes place in the combustor at temperature ranging from 800 to 950°C and at pressure 1.2–1.6 MPa.

The exhaust combustion products from the combustor pass through two stages of cyclone for cleaning them from fly ash particles. The exhaust products expand in the gas turbine. The gas turbine drives the compressor and the electrical power generator.

The exhaust combustion products from the gas turbine pass over the heat exchangers (economiser) where the gases are cooled to the desired temperature heating up the boiler feed water. The flue gases pass through the ash filter and enter the stack.

Ash is removed from the combustor bed and cyclones through the heat exchangers.

One of the main elements of the PFBC unit is the fluidised bed boiler, placed into the steel pressure vessel.

The location of the heat transfer surfaces of the steam cycle in the fluidised bed is peculiar to the bubbling bed. The specific volume of gas is small due to the over pressure and therefore the gas velocity in the fluidised bed stays below 1m/s, guaranteeing the low wearing of the heating surfaces. The height of the bed is 3.5–4 m. The bed heat load is controlled by the bed mass and height using the bed material reserve in the bunker.

The combustion products from the boiler strike to a two-stage cyclone block (as a rule) or after cyclones to ceramic hot-gas filters for cleaning fly ash. The dust-collection efficiency of two cyclones placed in succession is 98–99%. When ceramic hot-gas filters are used, the concentration of the solids in the flue gas is approximately 10 mg/m^3.

To use the heat from the bottom ash of the combustor and the cyclones heat exchangers that transfer heat from the ash to the water, are applied. The flue gas flows out from the boiler through a concentric tube cooled by the air from a blower. Air strikes to the boiler vessel, where it is divided into the primary and secondary air, cooling the boiler vessel and other elements of the boiler.

A gas turbine is designed specially for the operation with a high concentration of ash on the combustion gas. The gas from the turbine outlet with temperature 120–140°C strikes to the heat exchanger and transfers its heat to the feed-water. The gas from the economiser outlet is cleaned from fly ash in baghouse filters or electrostatic precipitators.

Another type of PFB is based on the circulating fluidised bed installation. A possible scheme of using this technology is presented in Figure 27.

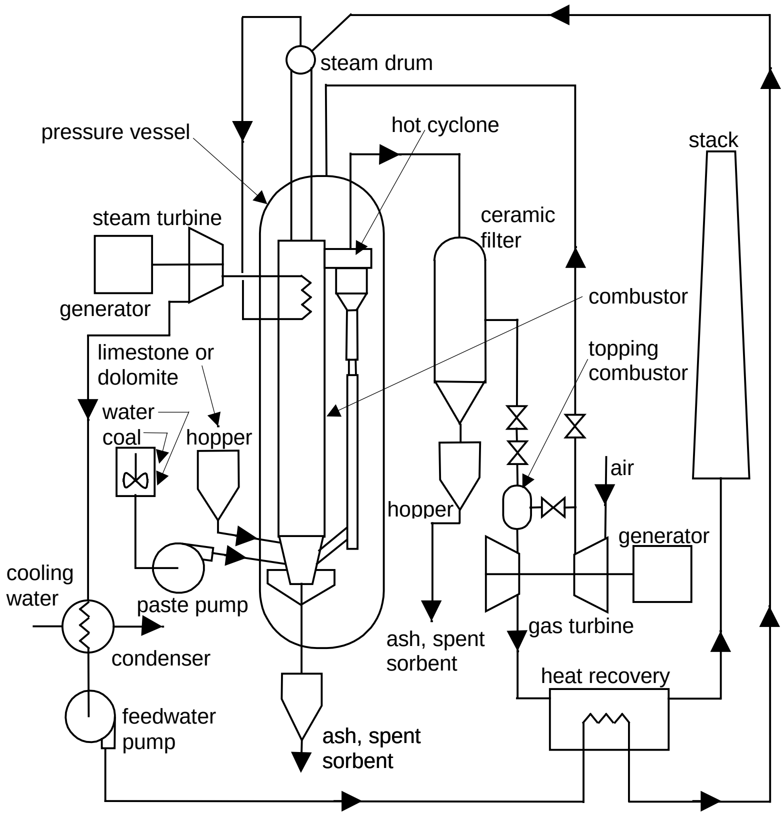
A remarkably high velocity in the combustor (3–5 m/s) and absence of heat transfer surface in the bed are peculiarities of the circulating fluidised bed PFBC. Heat transfer surfaces are placed out of the bed in the upper part of the combustor. The combustor together with the cyclone forms the circulating loop. This circulation increases the resident time of the fuel and sulphur oxides in the combustor. The total amount of the fuel and the ratio of primary and secondary air control the load of the unit. This prevents the use of bunkers for bed material compared to the bubbling fluidised bed. In this case the height of the bed does not affect the heat transfer conditions in the combustor. Therefore, a high temperature of the combustion gas in the boiler outlet is guaranteed also at low loads.

As shown on the scheme presented in Figure 27 the ceramic hot-gas filter is located after the cyclones for final cleaning of the combustion gas from fly ash. When a ceramic hot-gas filter is used, there is no need for gas cleaning equipment at the stack inlet.

The topping combustor before the gas turbine, which gives a possibility to increase the unit capacity at peak load, is peculiar to this scheme.

By replacing the PF technology with the PFBC combined-cycle technique for power generation from oil shale and applying superheated steam temperature 540/540°C and pressure 14 MPa, it is possible to increase the power unit efficiency up to 43–46%. To replace the 200 MW_e PF oil shale power-generating unit by PFBC boilers (with gas turbines) investments of about 9000–9500 EEK/kW are required.

Figure 27 Scheme of a heat power engine of circulating fluidised bed PFBC



Proceeding from the following composition of oil shale:

$Q_l^r = 8.3$ MJ/kg	$W^r = 11.2\%$	$A^r = 45.7\%$	$(CO_2)_k^r = 17.5\%$

the power plant with PFBC combustion technique (η = 0.43, φ = 1, k_{CO_2} = 0.3) is characterised by the following parameters:

$b = 1.01$ kg/kW·h	$q = 8.38$ MJ/kW·h	$\rho_{CO_2} V_{CO_2} = 0.82$ kg/kg	$m_{CO_2} = 0.83$ kg/kW·h

Consequently, using the PFBC technique the specific emission of carbon dioxide will decrease more than 40% compared to oil shale PF combustion techniques.

9 Conclusions

1. The Estonian oil shale is a fuel with a high content of mineral matter. Approximately half of the mineral constituents are carbonate minerals.
2. The specific emission of carbon dioxide from an electrical power plant burning a solid fuel containing carbonate minerals (oil shale) is determined by three groups of parameters:(i) parameters describing the conversion efficiency of fuel energy to electrical power; (ii) organic and mineral carbon content; and (iii) mineral carbon behaviour in the fuel combustion process.

3. In the conditions of combustion under atmospheric pressure carbon dioxide backpressure in the combustion products is in the range 0.014–0.016 MPa. This is lower than CO_2 equilibrium pressure and thermal dissociation of carbonates is possible. The dissociation rate of carbonate minerals in case of pulverised firing (PF) technology of oil shale is in the range 0.96–0.99.

4. In pressurised combustion conditions (total pressure 1.2–1.5 MPa) carbon dioxide pressure in the combustion products is in the range 0.14–0.16 MPa. This is higher than CO_2 equilibrium pressure and thermal dissociation of carbonates is not possible. Decomposition of carbonates occurs to some extent due to reactions between calcium oxide, sulphur dioxide and sandy-clay minerals occurring in carbonates. The probable decomposition rate of carbonates in pressurised combustion of oil shale lies in the range 0.3–0.4.

5. Due to the low rate of carbonates decomposition the heating value of oil shale at burning in pressurised conditions is higher than at burning in atmospheric conditions.

6. Proceeding from the proximate annul average composition of oil shale as received basis utilised in the Estonian Power Plant in 1996 (Q_l^r = 8.4 MJ/kg, W^r = 11.2%, A^r = 46.1%, $(CO_2)_k^r$ = 18.3%), the specific emission of CO_2 is m_{CO_2} =1.35 kg/kW·h.

7. The decomposition rate of carbonate minerals when burning oil shale in an atmospheric circulating fluidised bed combustor (ACFBC) is in the range 0.88–0.92 and the specific emission of CO_2 is m_{CO_2} = 1.16 kg/kW·h. Carbon dioxide specific emission by using the ACFBC technique decreases 14-–16% compared to the PF technique.

8. Proceeding from the following composition of oil shale: Q_l^r = 8.3 MJ/kg, W^r = 11.2%, A^r = 45.7%, $(CO_2)_k^r$ = 17.5%, the power plant with pressurised fluidised bed combustion (PFBC) technique has the specific emission of CO_2 m_{CO_2} = 0.83 kg/kW·h. Specific emission of carbon dioxide using the PFBC technique decreases over 40% compared to oil shale PF combustion techniques.

Renewable Energy Potential, Sources and Economic Efficiency

1 General overview

During the period when Estonia was part of the Soviet Union Estonian energy consumption was based on highly subsidised and therefore very cheap energy, common for the whole Soviet Union. Now prices of imported fuels, including from Russia, are on the level of world market.

Estonia does not have any domestic production of natural gas, oil and coal. Those fuels have to be purchased at world market price levels. However, oil shale is a substantial domestic primary fuel resource and its use will continue in the future. This will significantly contribute to the security of energy supply and will maintain independence from imported energy.

In recent years different kinds of renewable energy sources have become attractive in many countries. The renewables are supposed to be sources with a geophysical background, such as hydro-, solar and wind energy, and organic fuels with a biological background, such as firewood, wood chips, litter, waste and conditionally also peat, which is restored very slowly.

In world power engineering renewables are attracting increasingly more attention. The problems of using non-renewable energy sources like nuclear energy and relatively less polluting natural gas compared to coal or oil, could also be interesting in terms of reducing greenhouse gases. The transition to wider exploitation of renewables can be made step by step, after solving several scientific and technical (technological), financial, economic, social and political problems, as it will take place in case of transition to any other new energy generation technology, also in case of changeover to nuclear energy. New energy sources cannot yet (and so for a long time) replace all the fossil fuels used in power generation. In case of wind and solar energy the reason is the varying power of sources, their low concentration and the need to accumulate big amounts of energy. The generation of hydroenergy is limited by the shortage of water resources. Nuclear energy could be used in large energy systems with centralised distribution; however, it always involves threats and if possible, the use of nuclear energy should be avoided.

For commercial production of thermal and electric energy wind energy and biomass and also hydro power (which has less resources) are applicable in Estonia. Direct use of solar energy for commercial purposes is in principle feasible, but in our latitude it is not economically competitive with any other renewable energy resource.

In Estonia, which is surrounded by water from three-quarters and therefore rather open to winds, the wind power seems to be the most interesting and promising. Wind energy is renewable, clean and may potentially provide reduced emission of greenhouse gases. In Germany, for example, where the implementation of wind energy has been very quick and extensive, from 1974 till to day the use of wind energy for producing electricity has reduced the emission of CO_2 about 3.42 million tonnes, SO_2 21.8 thousand and NO_x more than 8.5 thousand tonnes (Wind Kraft Journal, 1998).

2 Objectives

Different renewable energy sources will be considered as part of general energy production. Prospects for wind, hydro- and biomass energy will be analysed according to Estonian conditions. Attention will be focused on opportunities to avoid the emission of GHG and other pollutants as compared with energy generation based on non-renewable energy sources and traditionally on oil shale.

The detailed analysis will include a technical description of wind energy technologies, combustion technologies for biomass, capital and operating costs per MW·h, harmful effects to the environment, including the emissions of direct GHG and other pollutants. A special chapter is devoted to research on wind conditions for harvesting wind power and estimation of wind energy potential in Estonia. The analysis is based on Estonian Wind Atlas, compiled at the University of Tartu.

The present material includes the development strategy of Estonian energy with a scenario of extensive use of renewable energy sources, with particular emphasis on the utilisation of wind resources. Recommendations are based on economic calculations.

3 Firewood

According to the latest estimations about 48% of Estonia's area is covered with forest and bush-land, which makes up approximately 2.02 Mha. The total volume of growing wood stock in Estonia's forests is about 350 Mm^3, while in recent years the annual cut was about 3–3.5 Mm^3. In addition to productive forest land, shrubbery on the former fields cover 200–300 thousand ha, where 1–1.5 Mm^3 of firewood could be supplied. About one third of the harvested wood is used as firewood, the remaining two thirds is processed in the woodworking industry (Estonian Energy..., 1995). The total growing stock gives 66–75% wood; branches, stumps and bark or the so-called logging residues form 25–33%. About 35–40% of timber becomes the residue of the wood industry (bark, saw dust and shavings) (Kiipsaar et al., 1992). In 1994, the harvesting totalled 3.62 Mm^3 (Statistical yearbook..., 1995) including 1.4 Mm^3 firewood, i.e., 39% (10.9 PJ) of the total harvesting; and 0.28 Mm^3 (1.8 PJ) for processing into wood chips, i.e., about 10% of the wood waste. Wood chips are used in local boiler houses. The caloric value of wood is 11.5 MJ/kg (at 30% moisture). It is estimated that 22–35 PJ of wood fuel could be used annually in Estonia (Biomass Technology, 1995).

Although wood is considered to be a clean energy source with regard to GHG emission, its use has a severe impact on the natural environment. For most species the conventional harvesting of firewood is the most critical operation. Wood harvesting damages the plant cover and changes drastically the ecological conditions in the forest area as well as in adjacent areas. Plant species composition is changed in most of the cases. The additional impact caused by the extraction of tops and branches is less critical. Wildlife is seriously disturbed by conventional forestry operations, especially by clear cutting and by selective thinning, if also all old and dead trees are cut and extracted. Operations with heavy machines may cause severe damages to soil and plant cover. Traffic intensity will increase, which may be disturbing in densely built-up areas. Wear and damages to the road network will increase, especially to forest roads when used in early spring. Road maintenance costs will increase significantly.

The net contribution of CO_2 emissions from biofuels can be considered to be negligible in view of the CO_2 uptake through photosynthesis. The emission levels of CO and hydrocarbons are mostly dependent on the combustion conditions and can be kept relatively low with a well controlled combustion process. The particle emissions can be higher than for oil and coal firing in spite of the lower ash content of wood, and thus cleaning equipment should be considered.

Using wood for combustion in boilers will reduce SO_x emission compared to heavy fuel oil and coal combustion to zero as wood fuels practically do not contain sulphur. Also NO_x emissions will be reduced compared to heavy fuel oil and coal combustion. The nitrogen content in wood is fairly low. However, the NO_x emission is strongly dependent on the combustion conditions and thus a higher emission level may occur under certain combustion conditions.

4 Peat

Approximately 22% of Estonia's territory is covered with wetlands. There are about 1600 peat deposits in Estonia and the resources make up about 2,400 million tonnes (as of 1 January 1991). The resources of peat for combustion are estimated at 2646 PJ (at 40% moisture) and the production capacity is 58.49 PJ (Estonia: Sector..., 1994; Biomass technology, 1995). In 1994, the primary energy supply from peat was 4.29 PJ. Peat is used as peat briquette, pressed peat, and sod peat. Peat briquette is mostly used in households. Pressed peat and the recent sod peat are burned in boilers of central heating systems. The calorific value of peat briquette is approximately 17.3 MJ/kg, that of pressed peat 12.6 MJ/kg (at 30% moisture), and of sod peat 8.9 MJ/kg (at 45% moisture).

The use of peat is associated with a strong impact on the environment. Opening up new peat production sites will drastically change the landscape and the aesthetic value of the area. Other uses of the peatland will become impossible. Peat harvesting destroys the plant cover of peat fields. Drainage will influence larger areas, where the conditions for plant growth may improve. Drastic effects occur when all vegetation is removed before harvesting on former virgin peat lands. Comparably smaller effects occur on already drained peatlands. The groundwater table can be lowered locally in connection with draining virgin peatland. High water flow and intensive rainfall cause erosion of harvested areas. Substantial fire hazards exist during summer, which is the only production period. Fires can be caused by self-ignition in peat storage, by machines, etc. Due to high transport needs the traffic intensity will increase. Wear and damages to the road network will increase, especially to forest roads when used in spring. Road maintenance costs will increase. Transport, processing and handling of peat fuels can cause high noise and dust levels. The risk for fire in storing is substantial.

The emission level of CO_2 is relatively high in peat combustion in relation to its heat content (carbon emission factor is 28.9 tC/TJ) (Greenhouse gas..., 1995). The emission levels of CO and hydrocarbons are mostly dependent on the combustion conditions and can be kept relatively low with a well controlled combustion process. Due to high and partly uncontrolled emission levels of particles the emission of heavy metals can be significant under certain circumstances. Heavy metals in high concentrations can be toxic for flora and fauna. The particle emission can be higher than that of oil and coal combustion and thus combustion gas cleaning equipment is strongly recommended.

The sulphur content of Estonian peat is on average 0.2–0.4%, but this value can vary significantly. However, the SO_2 emissions will be significantly reduced compared to heavy fuel oil and coal combustion. NO_x emission will not significantly change compared to fuel oil or coal. The nitrogen content of peat is usually fairly high, which can result in a relatively high emission level of NO_x. However, the NO_x emission is strongly dependent on the combustion conditions and thus extremely high levels of NO_x emissions can be prevented.

5 Prospects for the use of wood and peat

Wood and peat resources are available in Estonia for increasing the production and consumption of wood and peat fuels; however, imported fossil fuels can be substituted only to a certain extent. The trade balance will be improved, employment will increase and opportunities for entrepreneurship will be stimulated. Environmental impacts will mainly be positive, especially when considering the use of wood fuels and potential reductions in atmospheric emissions. Investments in fuel handling and boilers will be higher than for corresponding fossil fuel facilities. However, as most existing plants are old and worn out and have to be replaced within the near future, these expenditures are only slightly above those which would be required for the replacement with conventional technology. The utilisation of domestic wood raw material and peat as sources of fuel for heating systems, especially in small and medium-sized district heating plants should be increased.

6 Hydroenergy

6.1 Hydroenergy resources and utilisation

Estonian rivers have a relatively small water discharge and low gradient, which makes their energy potential moderate. Therefore there are no opportunities for building large and medium sized hydro units on the rivers. Nevertheless, a number of sites suitable for small hydropower plants can be found. Most of the suitable sites for establishing hydropower plants are situated in North Estonia where rivers falling from the limestone cliff have rapids on their lower courses, and in South Estonia where rivers starting from uplands have a relatively high gradient although their water discharge is small. Also some major rivers in Central and West Estonia have suitable sites for hydropower plants (the Pärnu, Kasari, Emajõgi, Põltsamaa).

Hydroelectric power made up a considerable share in the Estonian energy balance before World War II: in 1936 the capacity of hydroenergy units was 18.2% of the total capacity of power plants. The total capacity of hydroelectric stations was 9343 kW with the output of 28,770 MW·h. Over 900 small hydro turbines and water wheels were in operation. After the World War II importance of use of hydroenergy was decreasing, because of extensive development of oil shale power industry.

At present five small hydropower stations (Põltsamaa, Keila-Joa, Saesaare, Leevaku, Kotka) with the total capacity of 760 kW, and a number of very small plants with the capacity of only some kilowatts are in operation. The average rate of hydropower commissioning is about 0.2–0.3 MW per year.

The total theoretical resource of hydroenergy in Estonia is estimated at about 300 MW. From the point of view of power engineering the Narva River has the biggest discharge and power resource. The average discharge of the Narva River is 399 m^3/s, which outclasses the flows of all other rivers. The Narva Hydroelectric Power Plant with the capacity of 125 MW was built on the river in 1955. It is still in operation today and is now under Russian authority.

Based on the earlier assessments and latest calculations, technically feasible potential of all Estonian rivers, excluding the Narva River, can be estimated as high as 30 MW. Considering the resource location, the rivers in North Estonia - should be given the priority. That's because they are flowing on the limestone plateau and form waterfalls and rapids. Purtse, Kunda, Selja, Loobu, Valgejõe, Jägala, Pirita and Keila - each of them could give some hundreds kilowatts. Among the rivers falling into the Gulf of Riga, the Kasari and the Pärnu have the highest potential. In the middle course of the Pärnu River there are a number of sites, but only a few of them have a capacity up to some megawatts. In the watershed of Lake Peipsi falls with a capacity of about 100 kW can be found on many rivers (Emajõgi, Õhne, Ahja, Võhandu, Piusa, etc.). The potential of the Põltsamaa River is considerable, particularly on the territory of Põltsamaa municipality. Small suitable sites can be found on many streams all over the country.

There is still unused resource at Omuti site on the upper course of the Narva River with the capacity in the range of 15-–30 MW, which constitutes at least half of the total potential of all the other rivers. A power station at Omuti would allow seasonal regulation and the Linnamäe plant on the Jägala River daily regulation. In other sites opportunities for large storage basins are not available and they could be developed practically into run-of-river plants. The number of running hours for the installed capacity would be 5000–7000 on average.

Therefore, the total Estonian hydropower potential constitutes only 1–2% of the total capacity of power plants and is dissipated between a great number of small sites. Nevertheless, utilisation of this potential would enable to produce about 0.2–0.4 TW·h electricity.

6.2 The impact of hydroenergy

As known, small hydroelectric power plants have many advantages. Their technology is well developed and production cost is independent from inflation. Nearly full automation allows reduction the number of personnel and operation costs to minimum. Very small hydro plants do not consume resources - the water can still be used after flowing through the plant. Low capital costs and relatively simple construction operations allow to restore and build plants in a short time (in half to two years). The simple technology, small nonspecialised construction companies can be used, municipal or private funds engaged. The life time of hydropower plants is very long, often over 50 years.

Environmental impacts are small, unlike in the case of large hydroelectric power plants. On the contrary, small hydro plants improve water exchange and oxygen content in the water, improving thus the sanitary state of the river. Small storage lakes often make the landscape more picturesque and improve recreation possibilities. Proper minimal flows after the overflow dam and fish ladders warrant the minimal influence on the aquatic life. Overflow dams could be designed as natural rapids. Of course, small hydropower plants should be designed properly to match the surroundings.

Considering that the average fuel consumption of Estonian oil shale power plants is 17.4 GJ/kW·h and the average calorific value of oil shale 8.5 MJ/kg, the utilisation of the 30 MW hydropower potential would enable to save 0.2–0.3 Mt of oil shale per year. Further, considering that producing 1 kW·h of electricity in oil shale power plants yields about 10 g ash, 9 g SO_2 and 1 g NO_x, the use of 30 MW of hydropower allows to reduce pollution on average as follows: 1500 t ash, 1300 t SO_2 and 150 t NO_x per year.

The main disadvantage of small hydro plants is the dependence on the season and weather, although much less than in the case of wind or biomass utilisation. Nevertheless, the world practice shows that implementation of a new technology (submersible units, corrosion proof materials, modern control systems, inflatable dams, etc.) and continuous rise in the prices of fossil fuels make small hydropower plants in every respect more competitive. Their economic indices are better than those for wind or biomass utilisation.

The main obstacles in the development of hydropower plants are the same as for any other type of small renewable energy power plants:

- low price of electricity, which does not reflect the true cost of producing electricity;
- insufficient legislation regulating the relations with the public power system;
- poor access to capital and financing;
- insufficient supporting taxation policy;
- shortage of experience and know-how;
- unclear proprietary relations;
- most of the equipment should be imported.

6.3 Cost-efficiency of hydroenergy

In the study carried out by the Eesti Maaparandusprojekt in 1991, hydropower sites with the capacity over 50 kW, which could be of greatest interest in the near future, were picked out. These sites can be divided into two groups:

1. former power plants, fit to be restored - 24 sites with a total capacity of 4135 kW;
2. possible new plants - 22 with a total capacity of 3000 kW and the Omuti site. (Kaldamäe, 1991).

To ensure a reasonable pay-back time, which could satisfy small producers in the present situation where the prices on electricity are rather low, the specific investment costs must be low enough - in the range of EEK 5000–10,000 per year. Consequently, in the nearest future the plants of the first group will be of greater interest since there a considerable part of civil engineering structures have been preserved. As construction costs make up 40–60% of the total investment, their economic indices would be much better: according to rough estimates, the specific investment costs are about EEK 1000–12,000 per kW. The cascade of six plants on the Jägala River with a total capacity up to 3 MW, including the Linnamäe Plant with a capacity of 2–2.5 MW and with the possibility of daily regulation, should be main interest.

Construction of entirely new hydroelectric power plants will become profitable with a further growth of fossil fuel prices and increase in electricity prices. Specific investment costs for new plants are roughly estimated to be in the range of EEK 7,000–30,000 per kW. The lowest cost, about EEK 7,000 per kW, is estimated for the Omuti site.

Additional costs for building roads and transmission lines are not relevant due to the rather well developed infrastructure. At the same time small hydroelectric power plants, located all over the country, would enable to reduce transmission losses and improve the voltage quality.

To conclude, in the near future it is feasible to restore former small hydroelectric power plants with a total capacity of 4–5 MW, in the longer perspective it is possible to increase the total capacity of hydro plants up to 20–30 MW.

7 Wind energy

7.1 Introduction

Successful use of wind energy in several developed countries, rising electric energy prices and the need to reduce atmospheric pollution originating from the energy sector are the key issues why interest in wind energy shall increase in Estonia. Utilisation of wind energy may be especially attractive in coastal areas where difficulties in energy transmission from the main electrical network occur. On the islands that are not connected to the main electrical network the use of wind energy may provide a substantial amount of electricity and reduce the need for diesel fuel used for the generation of electricity.

Use of wind energy has been hindered so far by a systematic under-capacity operation and relatively low unit cost of energy (1.4–2.1 US cents per kW·h) of oil shale power plants. Wind energy cannot be an alternative but a supplement to our oil shale based or any other traditional fossil source power generation, e.g. to natural gas in the future. Wind turbines need a reserve for the calm times and they could be handled as additional energy producers.

7.2 Prerequisites for wind energy utilisation

To guarantee successful development of wind energy generation some significant prerequisites must exist and the general principles of the energy development strategy must be formed. In general the problems of large- or small-scale power generation based on wind energy should be viewed separately. The installations over 100 kW are considered among the large wind energy installations, they are used for the electrical energy generation to the main electrical network or to an autonomous system, also combined use with the production of heat or parallel work with a diesel generator is applied. The devices belonging to the set of small energy installations are mainly autonomous and used for the production of electrical or thermal energy. Currently the emphasis is on the large-scale power generation, and it is not dependent on the type (autonomous or network-connected) of the installations. The main reason is that a bigger wind turbine with a higher tower, common to several households is more efficient. Such a co-operation is especially popular in Denmark. The main prerequisites for the introduction of wind power generation are:

- sufficiency of the wind resource;
- nearness of the suitable consumers or high-voltage transmission lines;
- possibility to accumulate energy on autonomous installations;
- economic expedience;
- opportunity to employ local labour;
- possibility to produce installation's components on the basis of local industry;
- relationships between producer and consumer regulated with laws and rules;
- support of the residents and local authorities.

Actually the market regulates the situation if a wise tax policy is applied. For starting wind energy programs applying zero-taxation for imports of wind turbines and their components is essential, it should be possible to get long-term loans with moderate interest rate and the price for transmission should be limited (it could be 10–15% of the average transmission price) of the electrical energy. After two or three years the price of electrical energy will be so high that there should be enough local and foreign investors and the development of wind power generation will be normal, also the production of the machines will be started in Estonia. Especially local authorities in Saaremaa, Hiiumaa and Pärnu counties are interested in the use of wind energy. The development process can be accelerated by means of subsidies paid to wind energy producers from the nature protection fund, which raises money from the pollution tax.

The quantity of electrical energy generated in Estonia is approximately 10 TW·h per year. If we set the purpose to produce 5% of it by wind turbines and we expect that the operating time (annual availability) of wind turbines with rated power of about MW is 28.5% (that is 2500 hours per year) and that the cycle of installation is 20 years then we have to install wind turbines with total rated power of 10 MW every year. In other words: wind turbines with total capacity of 2.5 MW should be manufactured (initially in virtue of licences) and installed every three months in co-operation with foreign companies. The annual project cost is about US$ 9.6–10.8 million. The length of the cycle is determined by the exploitation time when all the equipment is renewed. This could be considered the maximum development program of Estonian wind power generation, although some surprises in free energy market are possible. For example, we could export wind generated electrical energy from south-west coastal regions at Pärnu to the Latvia, if the situation in the market is appropriate. No doubt the resources of wind in Estonia's islands and coastal areas are promising. In the next sections we will show that there are no technical or climatological (wind resource) restrictions to exceed the target set in maximum development program. Everything depends on the situation in the energy market, investments to start the new branch of production and energy policy.

7.3 Estonian wind resources

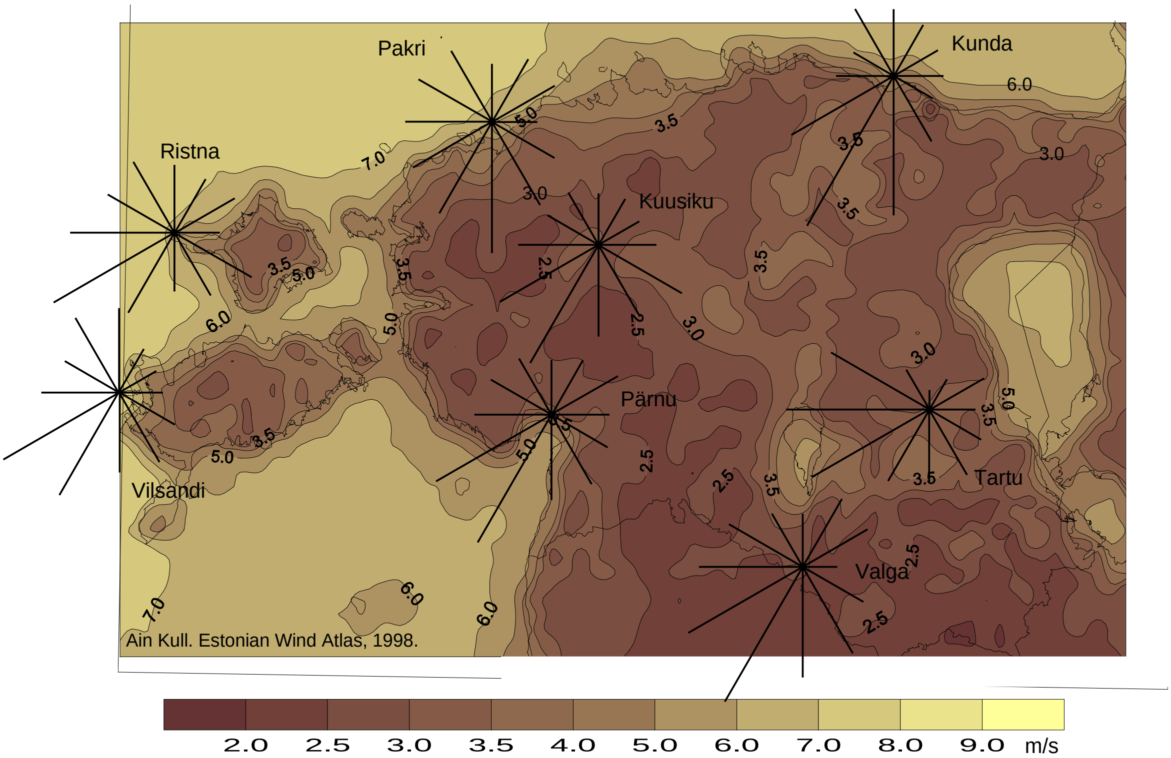
Estonia is situated on the eastern coast of the Baltic Sea. This is a region with intensive cyclonic activity and therefore with a relatively high mean wind speed. The general character of the Estonian wind regime is determined by atmospheric circulation and its seasonal variation over the Atlantic Ocean and Eurasia. However, the Baltic Sea itself is a very important factor affecting wind climate, it has an especially strong influence on the wind regime in coastal areas.

The results presented in this chapter are based on similar material and methods used for the European Wind Atlas (Troen and Petersen, 1989) where the influence of nearby sheltering obstacles, roughness and orography of the surrounding area are taken into account when modelling wind resources. More attention has been paid on modelling the spatial and temporal distribution of wind resources over the whole area of Estonia. The PC program WASP 4.0 (Wind Atlas Analysis and Application Program) worked out at Risø National Laboratory, Denmark, was used to perform the calculations.

Estonia has a favourably high density of meteorological stations, which provides a good possibility for analysing wind and wind energy resources in different regions. Based on the mean monthly wind statistics from 48 meteorological stations and measurement sites in the period 1891–1990 thirteen wind climate regions were distinguished. In these areas the meteorological stations with high-quality measurements and continuous time series were chosen to model wind resources. The nominal period for model runs was 10 years (01.01.1981 - 31.12.1990) where data sets consisting of observations after each 3 hour were used. For three stations climatologically long period frequency tabulations were used for validation. Because wind is a phenomenon that varies from year to year on a large scale, the time series of each meteorological station are of the same length and period. This eliminates relative deviations in territorial distribution of wind resources.

Differences in the territorial pattern of wind speed and directions in Estonia are caused mainly by its situation on the Baltic Sea. The impact of the sea leads to significant differences in wind speed between the coastal and inland parts of Estonia (Figure 28). The annual mean wind speed is up to 6–7 m/s at 10 m height in the West-Estonian Archipelago and in open coastal areas. A perceptible decrease in the mean wind speed can be observed in the narrow transition zone from the sea to land. The wind speed decreases by approximately 40% in the transition zone with an average width of 20 km. The mean wind speed is reduced in those areas by up to 4 m/s. Also, the number of days with storm or strong wind decreases rapidly from 40 days per year, characteristic of coastal areas and islands, to 10 days per year in the transition zone.

Figure 28 Mean annual wind speed at 10 m above ground level



In the coastal areas and on small islands the wind blows most frequently at a speed of 4–7 m/s, on the western coast of Saaremaa Island most frequently 4–8 m/s. In the inland parts of Estonia wind speed is most often up to 4 m/s. The mean wind speed on the northern coast of Estonia remains between 4 and 5 m/s. It is higher in the western part and decreases toward the east. The decrease in mean wind speed coincides with the increase in distance from the open sea and surface roughness in the neighbouring territories. Because of the cliff, the northern coast of Estonia clearly has a different influence on wind than any other part of the Estonian coast. In spite of the steep increase in the absolute and relative height of the ground level, the wind speed does not increase in the same extent. The abrupt change in roughness because of the cliff results in less influence on winds blowing along the cliff and more effect on winds blowing perpendicular to the cliff. The cliff's influence is especially strong on air moving perpendicularly from the sea to land. The uniform wind profile is disturbed and the uplifted air masses do not significantly increase speed. Consequently, the cliff and other escarpments do not cause a significant increase in mean wind speed.

In inland parts of Estonia the annual mean wind speed is low and strongly influenced by roughness and orography. At 10 m height it varies only slightly over large areas and remains between 2.5 and 4 m/s. Lower values of wind speed occur in regions with complex terrain and large forested areas. One such region with a low wind speed (2.5–3 m/s) extends from Pärnu to northern and north-eastern Estonia. Another large area with low wind speed extends from the Sakala Upland over the southern part of Estonia to south-eastern Estonia. Clearly different wind conditions prevail over Lake Peipsi and Võrtsjärv. The mean annual wind speed above Lake Võrtsjärv is up to 4.5 m/s. Lake Võrtsjärv and Lake Peipsi are connected by a belt of rather high wind speed (4 m/s) that lies over the east–west orientated valley of the Emajõgi River.

At a higher level, 50 m above ground level, the mean annual wind speed is dependent primarily on the distance from the coast. Over the Baltic Proper the mean wind speed exceeds 9 m/s, over the Gulf of Finland and the Gulf of Riga it remains 7–8 m/s. At this height above ground we can see clearly the influence of the West-Estonian Archipelago. Due to increased roughness the wind is weakened and the shelter of Saaremaa reaches the continental part of Estonia as a belt of lower wind speed. In inland areas of Estonia wind speed varies only slightly, remaining in most regions between 4 and 5 m/s. Only in south-eastern Estonia with its complex terrain, mean annual wind speed remains below 4 m/s. Lake Võrtsjärv differs only slightly from the surrounding areas, but Lake Peipsi is large enough to form an undisturbed wind profile and the mean annual wind speed at a height of 50 m is up to 7 m/s.

The temporal course of wind in winter depends mainly on the Icelandic Low and the Siberian High, when the horizontal gradient is steep and cyclonic activity is high. In summer differences in the baric field are smaller as the Icelandic Low weakens and the Azores High strengthens. A smaller horizontal pressure gradient and lower cyclonic activity lead to a lower wind speed. Therefore, the mean monthly wind speed has a clear temporal course with a higher value in winter. In winter the monthly mean wind speed on islands and on the western coast reaches 7–8.5 m/s, in the inland areas it remains between 4 and 5 m/s. The increase in wind speed in coastal regions is greater than in inland areas where wind is strongly influenced by forest and other sheltering features. As spring approaches, the frequency of higher speed of wind decreases and weaker winds, 2–4 m/s in inland or 3–6 m/s for coastal areas, become typical. In summer the monthly mean wind speed is the lowest and therefore also the differences in absolute values are smaller. On the western coast of the West-Estonian Archipelago the mean wind speed does not exceed 6 m/s and in the inland parts of Estonia it is up to 3–3.5 m/s. In summer the number of days with strong or stormy wind is low, in coastal areas 1 to 2 days per month, in the inland parts several summers without any stormy days may occur. In autumn a very rapid increase in the mean wind speed is characteristic and this is the season with the highest number of days with strong and stormy winds. In coastal regions strong and stormy winds often blow 5–6 days per month. Monthly wind speed attains its maximum (6–8 m/s) in the western part of Estonia earlier (October, November) than in the eastern part (December). The wind speed is also high in January, but decreases rapidly after February.

The daily course of wind speed is closely related with climate type. In regions with maritime climate the daily course has only a small range. In continental areas it is of much greater importance. Differences in wind speed are more essential in summer than in winter. Generally, the mean wind speed is higher in the afternoon and lower early in the morning. However, it should be taken into consideration that in winter the mean wind speed can be higher in the morning than in the afternoon. It is the case more often in coastal regions. Maritime climate is characterised by only a small variation in the mean monthly wind speed and especially in the daily course. The absolute differences in the mean wind speed between the observation terms with the highest and the lowest values are not in winter, when the mean wind speed is the highest, or in summer, when the relative differences are the greatest, but in late spring or early summer. Another period with high absolute differences is August. In continental areas the mean wind speed varies in April and May from 1.5 to 2.5 m/s and in August slightly less, from 1.5 to 2 m/s. In spite of the higher wind speed in coastal regions, the daily variation of the mean wind speed has the same or even smaller range (from 0.2 to 2 m/s).

An important characteristic for wind engineering is the number of calm days. On the western coast of the West-Estonian Archipelago the annual number of days with calm is 5 to 10. On the southern coast of the Gulf of Finland the number of days with calm increases from west to east, correspondingly from 20 to 65 days. In the western part, influenced by the Baltic Proper, the number of days with calm differs only slightly in winter (1 to 2 days per month) or summer (3 days per month). In the eastern part a clear seasonal pattern can be observed with 2–5 calm days per month in winter and 7–11 days per month in summer. The number of calm days is the highest in south-eastern Estonia, where calms can be observed up to 90 days per year. The number of days with calm per month is up to 6 days in winter and 10–14 days in summer.

The mean energy density in wind and the available wind energy production are closely related with temporal and spatial wind distribution. The mean energy density (W/m^2) is a wind energy characteristic that is proportional to the third power of wind speed and describes energy available in a flow of air through a unit area. Its temporal course is quite similar to the mean wind speed, but depends more on wind speed distribution. A greater wind speed variation can be observed in coastal areas, while inland parts of Estonia have a more even wind distribution with a higher occurrence of wind speed in lower wind speed classes. Therefore the mean energy density in coastal regions is considerably higher than in inland areas. The mean energy density is a characteristic which has practical importance in regional assessment of wind energy. Using wind turbine swept area and conversion efficiency the mean energy density gives an approximate value of the actual potential wind generated power. On the western coast of the West-Estonian Archipelago the mean energy density is up to 550 W/m^2 at 10 m height above ground level and decreases rapidly from west to east and from the sea to inland areas. In inland areas the energy density is relatively low, between 25 and 50 W/m^2 and increases from south-eastern Estonia toward north-western Estonia. At a higher level the mean energy density increases as the influence of topography on wind speed decreases. On the coast of the West-Estonian Archipelago it reaches 700 W/m^2 at 30 m above ground level. In inland parts of islands or continental areas the amount of energy in wind is much smaller. The increase in the mean energy density with increasing altitude is greater over islands and coastal regions. Inner parts of Saaremaa and Hiiumaa have mean annual energy densities at 30 m height of 150–250 W/m^2. In most parts of continental Estonia this energy value is between 50 and 100 W/m^2. Only Lake Võrtsjärv and Lake Peipsi have higher energy densities approaching 200 W/m^2 on the coast of Lake Peipsi. The mean energy density is closely related to wind turbulence, therefore it has somewhat smaller differences in territorial and seasonal variation compared to the mean wind speed. Table 23 gives an overview of the variation of the mean monthly energy density in different regions by corresponding meteorological stations. The values are modelled at 35 m height above ground level (the most usual hub height of wind turbines) for these sites.

Energy density attains its maximum in late autumn, earlier in coastal regions (October, November), later in inland areas (December, January). When the maximum is attained, the variation between different months is small. In February and March (in eastern part of Estonia also April), the mean monthly energy density is only 60–75% of that in winter. The reduction in energy is most considerable in the West-Estonian Archipelago, but southern Estonia has almost as high an energy value as in winter. The lowest monthly values are characteristic of late spring and summer, from May to July. Based on the data of the Vilsandi station, the mean monthly energy density in May is only 29% of that in December. A similar rate (25–35%) can be observed also in other regions when the periods with the highest and the lowest energy are compared. A rapid increase in mean monthly energy density takes place in August and September. Within three months in autumn on the western coast of Saaremaa and Hiiumaa the monthly mean energy density can rise from 350 to 1100 W/m². The more wind is influenced by islands and the mainland, the smaller is the annual variation. In most coastal areas monthly values in summer are 150–200 W/m² and 350–700 W/m² in winter. The energy density in inland Estonia is very low, especially in southern and south-eastern Estonia, where it is up to 30 W/m² in summer months and usually below 100 W/m² in winter.

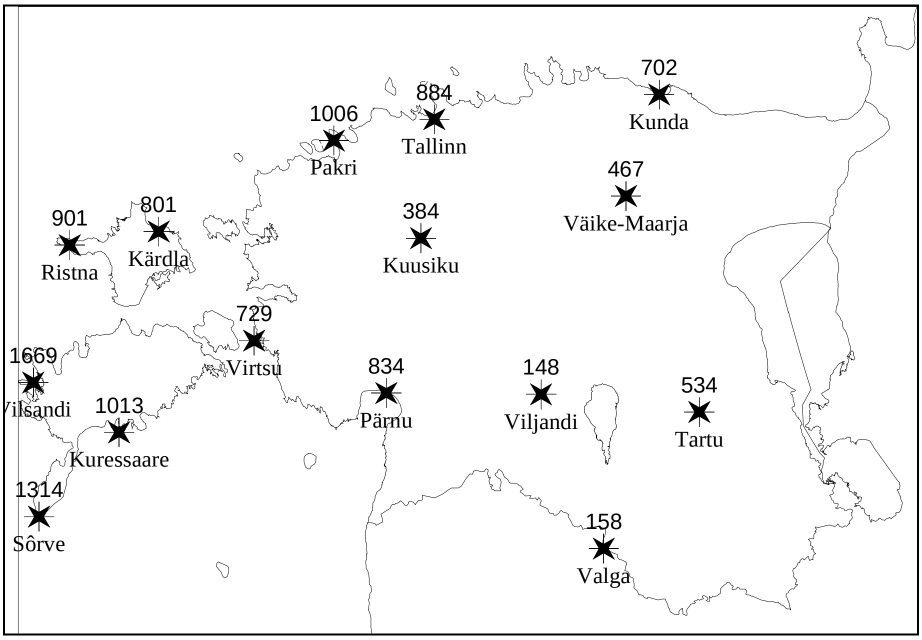
Table 23 Mean monthly energy density (W/m²) at 35 m above ground level

Meteostation	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I-XII
Vilsandi	1048	648	610	484	316	387	363	557	723	968	1090	1091	690
Kuressaare	535	367	318	240	208	222	186	230	275	417	393	406	314
Pakri	432	310	284	235	167	164	151	231	295	419	447	439	309
Ristna	426	260	221	152	110	134	134	212	321	446	452	442	280
Pärnu	407	237	214	146	138	166	164	229	265	369	331	309	267
Kärdla	324	246	216	216	141	191	144	171	217	264	333	337	232
Virtsu	254	189	177	166	144	172	142	179	202	258	295	280	202
Kunda	287	176	155	180	110	130	93	142	198	278	379	294	199
Tartu	228	175	151	158	112	94	69	87	108	163	173	167	141
Väike-Maarja	186	124	127	121	98	89	67	86	111	153	179	162	124
Kuusiku	152	111	120	131	92	77	52	56	84	121	130	149	106
Valga	79	62	63	62	42	32	22	30	35	55	62	65	50
Viljandi	64	56	55	56	40	36	25	30	37	58	62	61	48

Using power curves of wind turbines with different rated power output, the available wind energy production was calculated. Results presented in Figure 29 show mean annual wind power production by wind turbines with rated power output 450 kW at sites of meteorological measurements and in present conditions.

The best sites, primarily on the western coast of the West-Estonian Archipelago, can be characterised by mean annual energy production greater than 600 MW·h/yr. by a 250 kW turbine. In coastal areas and on islands there are many sites where annual production could be up to 400 MW·h/yr. Smaller expected power output is characteristic of inner parts of Estonia (100–200 MW·h/yr.), especially for southern Estonia. The biggest territorial differences in power output are related to wind turbines with higher rated power output. In the western coast of the archipelago the available wind energy production with a 450 kW wind turbine can exceed 1600 MW·h/yr., but in southern Estonia it remains below 250 MW·h/yr. The highest power potential was found in the western part of Estonia and on islands. These are also the most distant areas from the currently used oil-shale fired power plants.

Figure 29 Mean annual energy production (MW·h/year) by wind turbine with rated power 450 kW



7.4 Exploitation of wind resources

Besides wind resources and technical solutions, which set limits on the wind power production, there are several other factors that affect wide exploitation of the climatologically available wind energy. The main limiting factors in addition to economic and technical ones are related to land use, wildlife, landscape aesthetics and safety requirements.

Most common uncertainties associated with wind energy are related to wildlife, especially to aviofauna. Wind power plants may have a direct influence (injury or death of birds due to collision with blades or tower) and an indirect effect through the disturbance of birds' breeding, nesting and feeding places, but also by affecting their migration behaviour. However, several studies carried out in Germany and The Netherlands show that in general mechanical effects on bird life are not very strong. Death of birds occurs only in case of extreme weather conditions (low clouds, dense fog or heavy rainfall with strong wind) and mainly at large wind farms. The small number of injured birds can be explained by the fact that birds avoid wind farms on their migration routes; however, most bird species show fast habituation to wind turbines. Still, t should be considered that a change in birds' migration routes would strongly affect their normal life and therefore the main migration routes, breeding and nesting areas should be excluded from the list of suitable areas for wind power production. The influence of wind turbines on animals and plants is only minor, mainly limited with the construction period and service roads. No change in animal habitation has been observed at wind farms.

The operation of a wind power plant inevitably brings about noise emission and moving shadows of blades on sunny days. Noise emission is strongly dependent on the size and construction type of the power plant, but disturbance is more important at inland sites than close to the coast, where the sound of the waves and other background noise due to higher wind speed make the noise of the wind turbine less noticeable. To keep the noise level acceptable, the distance between residential buildings and the wind turbine should be not less than 400 m in open land, which corresponds to noise <40 dB(A) that is lower than in a normal living room (50 dB(A)) but louder than the bedroom level (30 dB(A)) (Freris, 1992). Moving shadows of the blades are felt to be disturbing in the morning and evening when sun rays are at a low angle. However, in certain circumstances wind turbines can affect also the visibility of navigational signs (and lighthouses), therefore some sectors close to these should not be used for siting wind turbines.

The land use intensity by wind turbines is relatively small being determined mainly by the size of the foundation of the plant, the area of the service roads and electric power lines. All the rest of the area can still be left in natural condition or to be used for other purposes. However, one should consider with some restrictions the surroundings of a wind farm or a power plant due to safety reasons. No activities demanding frequent stay of people or having living facilities close to wind turbines can be allowed because of possible damage caused by blades. Also icing of blades is common in winter in Estonian climate and pieces of ice can injure people.

Landscape aesthetics can be regarded as a subjective restriction in wind energy planning because it does not have any harmful results on living beings. Since the most appropriate sites for wind power plants are in wide open areas their visual impact can be a disturbance to the landscape. Thus wind turbines should be fitted into the landscape as well as possible and areas with unique natural landscapes should not be used for this purpose. Also recreational areas should be left out of use for wind power generation because of a combination of questions of landscape aesthetics, land use and safety.

To promote sustainable exploitation of wind resources it is important to figure out the most favourable sites and areas for wind power plants in the early stage of planning. Acceptable sites are only those which are economically profitable (i.e., good wind conditions) and do not conflict with environmental and public interests. Climatologically the most favourable areas for wind energy are shown in Figure 29. Using the zoning concept different areas can be distinguished in respect to suitability for wind power production. Mean energy density maps serve as basis and due to the above-mentioned negative criteria regions with (a) no planning restrictions, (b) areas with restrictions and (c) exclusion areas are defined. In no circumstances are wind turbines allowed to be sited in exclusion areas (like settlements, nature reserves, etc.). Restricted areas are not recommended but under certain conditions still available for the generation of wind energy. Siting of wind turbines in such areas depends on local authorities and decision makers because it conflicts with one or more functions of the area (e.g., recreational function). In general harnessing of wind energy in a restricted zone should be avoided as long as areas with no planning restrictions are available. Areas with no planning restrictions can be divided further into favourable, suitable and unfavourable areas according to wind resources, infrastructure, distance to consumer, etc.

A case study carried out on Saaremaa, the biggest island of the West-Estonian Archipelago, shows that no planning restrictions are set for 29% (786 km^2) of its area, areas with planning restrictions (including forests) include 56% (1508 km^2) and exclusion areas for wind energy generation make up 15% (418 km^2) of the total area of Saaremaa (2713 km^2). Saaremaa, which is part of the West-Estonian Archipelago Biosphere Reserve and a well-known recreational area, has a relatively high share of factors restricting the use of wind energy. Its coastal zone with the mean annual wind speed at 50 m above ground level 6.5–9.0 m/s can be described by the following figures: areas with no planning restriction comprise 35%, areas with restrictions 39% and exclusion areas 26% of the zone. In total about 5% (126 km^2) of the area of the island classifies as climatologically most favourable (mean annual wind speed at 50 m a.g.l. 6.5–9.0 m/s) and with no planning restriction (Steinrücke et al., 1996). If one wind turbine with rated power of 500 kW per 2 km^2 is erected, then only the most favourable coastal areas without planning restrictions can provide enough place for 63 wind power plants. The low estimation of mean annual energy production by this type of wind turbines in this area is 1200 MW·h per year. Thus the 63 turbines can produce 75,600 MW·h wind energy per year and only the most favourable sites would be used. However, this amount makes up about 70% of the present energy consumption on Saaremaa (less than 105 MW·h/yr.) and it is much higher than the capacity of the electric network.

Rough estimations on the second biggest island of the West-Estonian Archipelago, Hiiumaa, show that due to various types of land use and settlements the proportion of exclusion areas for wind energy in the coastal zone is somewhat lower (15–20%) than in Saaremaa, but the share of areas with restrictions is higher, mainly due to higher percentage of forest area.

The lowest share of exclusion areas in the coastal zone with very good wind resources can be found in the north-western part of Estonia where the exclusion areas are estimated to account for about 10%. Restriction areas make up 40%, and 50% of the coastal zone can be treated as favourable for wind power production. On the west coast and in south-west Estonia the share of exclusion and restriction areas increases, mainly because of nature reserves, birds' migration routes, recreational areas and settlements.

On the northern coast the main restrictions are connected with settlements, but also less favourable wind conditions make this region less attractive than western Estonia. In spite of several areas without planning restrictions inland areas are not recommended for large scale wind energy production due to low wind speed and thus low economic efficiency.

In general one can state that Estonia has more space available for wind turbines than is needed to produce 10% of the current electric energy production in Estonia. To avoid ineffective land use of favourable areas and to minimise objective or subjective negative impacts of harnessing wind energy modern medium and large scale wind power plants should be preferred.

7.5 Perspectives for wind energy in total energy production

The most important principles observed in this report are the following:

- The base load will be covered by oil shale power plants located in Narva. The load changes of those power plants are planned a long time before and their equipment should work at optimal load with respect to pollution as well as other parameters. If the situation demands, other fuels (like oil shale and coal mixture or gas etc.) could be used after respective reconstruction.
- To cover the peak load of the network some small gas turbine power plants will be installed in addition to the thermal power plants in towns (Iru, Kohtla-Järve, Ahtme) which can use natural gas, light oil and shale oil. The load limits the power of the gas turbines with a combined cycle: this is a very big problem during summer. It is possible to apply several gas turbines having different power.

- To guarantee the reserve small-powered energy devices with a Combined Heat and Power (CHP) cycle (like steam turbines, turbine generators that use local fuels such as wood chips, peat, straw, waste, biogas or diesel generators that use rape biooil or biogas) could be installed in large factories and district heating boiler houses.
- Pilot wind power plants will be established. For example, plants will be erected on the Sõrve Peninsula, Saaremaa (2.5 MW), in Kõrgessaare, Hiiumaa (1.5 MW), near Pärnu (Liu) and in Paljassaare near Tallinn (1–3 MW, equipment could be partly produced in Estonia); using finances and support from the state budget, private capital, EU's programs (PHARE, THERMIE), several foundations from aboard and from Estonia. After analysing the exploitation of those pilot programs, a decision will be made about the continuation of the development of wind power generation. If there are investors, large wind farms may be established in other regions; however, areas with most favourable conditions should be recommended.
- Unlike other energy production methods the wind power generation could be applied step by step adding relatively small units (200–600 kW). This enables to finance suitably the setting up of the wind power plants: public as well as private corporations (also societies) could be formed. Local inhabitants, who are consuming the energy generated and could be employed as builders and maintenance personnel, could be also shareholders of the wind power plant. Government can affect the private capital's participation in wind power plant projects, for example by exempting investors from taxes and supporting wind power researches at institutes.
- On the islands that are not connected to the electric network combined wind–diesel devices should be installed, primarily on Ruhnu, Prangli and Naissaar. Considering relatively small rate of load and power of the existing generators, the best are 25–200 kW generators. The controlling requirements set to wind turbines working in such power plants are strict. That is the main cause why the wind turbines with pitch controlling (turbine with regulated blade pitch) like an Enercon E-30 or Vestas V27 and V29 (225 kW) are preferred. The construction of the prototype is possible in co-operation with foreign companies (licences, complicated parts, main computer with programs) and local factories (Ilmarine, Volta, Naviplast etc.) and Tallinn Technical University. The production of large metal parts (tower, metal frame or bedplate, gearbox, main shaft, yaw ring, brakes) could be arranged here. Blades should be bought from Denmark (LM, Vestas) or Germany (Enercon). The production of blades is conceivable in Estonia too, if the licence is obtained, also the generator could be made in co-operation with foreign companies.
- To stimulate the use of local fuels, wind and hydroelectric power, the parliament and government should apply complementary procedures to ensure that the energy law would guarantee that the energy produced on the basis of such sources has a guaranteed lowest price on the selling to the electrical network or maximum transmission fee. This could be 5–15% of the average electricity price (without VAT) and depend on transmission distance; correspondingly the minimum wholesale price would be 85–95% of the average electricity cost. Furthermore it is important to initiate a special law so that the imported machinery (generators, turbines, windmills etc.) and that produced in Estonia will be tax-free within the next 8–10 years. Without such a warranty the development of wind energy will probably not start because of low profitability with the current energy prices which do not stimulate investment.

- During the introduction of wind energy wind turbines of the kind that are capable (by improving the proportion between active and reactive power; controlling the voltage and frequency) to support the operation of the electrical network; especially in marginal regions like islands, should be used. Those requirements are fulfilled in the best way by wind turbines Enercon E-66 (1500 kW), E-40 (500 kW) and Vestas V-63 (1650 kW) and V-44 (660 kW). Also the application of electrical heating through the electrical network should be promoted.
- In developing the energy production strategy it should be taken into consideration that the resources of wind and hydropower and the existing infrastructure allow their growth in the total energy production to up to 3% (installed power could be raised up to 10%) without any serious problems. Modern wind turbines (those mentioned above and also others) are adjusted to improve the operation of unstable networks and their application could raise the part of wind electricity far over the value mentioned above.

To investigate obstacles to the implementation of the principles described above and complementary circumstances a team financed from the state budget should be formed; also this team should make the necessary economic calculations and wide-ranging analysis.

7.6 Development plan for starting wind energy utilisation

As a first step, investments for research and study of foreign experiences on wind energy utilisation are needed. Know-how is necessary both for the planning of wind energy utilisation and building up the capacity for domestic wind turbine production. In the early stage this means close co-operation between research institutions in Estonia and other countries to create a favourable background for wind utilisation. The best way is to organise a governmentally financed renewable energy knowledge centre with the main task to co-ordinate activities between different stakeholders. The main problems should be solved as a joint effort of different organisations before intensive use of wind energy can start. It is necessary to specify promising areas for harnessing wind energy, to develop the legislative background (taxation, etc.) and create basis for technical support. To achieve these objectives an extensive support from the state budget is needed. Also erecting first wind turbines cannot usually base on private investments but some governmental (through taxation) and international subvention should accompany. The wind turbines and wind farms established first should serve also as pilot projects providing well recorded data about turbine operation. At present there is limited experience with wind energy in Estonia. There is only one grid connected wind turbine, which has been working at Tahkuna (Hiiumaa Island) since August 1997. The pilot wind turbines and wind farms would be good basis to demonstrate the perspectives of wind power, teach and train specialists in wind energy, organise courses for local energy management and popularise wind energy. The experimental wind turbines and wind farms will not be only a research and demonstration object but being sufficiently powerful they will be used for commercial energy production. It is evident that after establishing wind farms and pilot wind turbines interest in wind energy among local investors will be sufficiently aroused.

It is not possible to use foreign finances in the long run but for the realisation of pilot projects these are needed. As a rule the funding of such projects by foreign organisations does not exceed 30–70% of the project cost. As an example, the first middle-class wind turbine in Estonia (150 kW Danish GENVIND at Tahkuna) was financed 85% from the Danish Environment Protection Agency and 15% from the

Estonian Environment Foundation. Presently research on the implementation strategy for the utilisation of wind energy in Estonia is carried out. The first phase of this work (Pre-feasibility Study and Project Identification) was made by Danish and Finnish organisations in co-operation with Tallinn Technical University. Economic calculations show that the cost of wind produced electricity is decreasing. At the same time the costs of electricity produced in our oil shale fired power plants are increasing. A large part of the price of electricity is the result of transmission losses, which can be reduced if wind energy is used. Harvesting wind energy enables electricity production closer to consumers, especially in West Estonia, the most distant area from the oil shale power plants. Our calculations show that electricity produced by wind turbines will be competitive in the near future. Therefore it is the right time to start with funding projects to demonstrate the prospects of wind energy in the future. To get higher efficiency only siting of modern medium- or large-scale turbines for commercial energy production should be recommended.

Before intensive siting of wind turbines most favourable sites (taking into consideration both wind resources, socio-economic and environmental aspects) should be defined to avoid conflicts between different stakeholders. Well defined sites are a must for wind farms which are usually more cost effective, but also may affect local conditions more than stand alone wind turbines. Severe foreign experiences show that building costs are lower for greater (500–1650 kW) wind turbines, especially when concentrating them in large wind farms. There are already some groups of foreign investors who are interested in founding wind farms in Estonian coastal areas. So far the main obstacle has been the relatively low price of electricity and unfavourable set of laws for the use of alternative energy sources.

The best wind conditions in Estonia are found on the West Estonian islands. Therefore the first wind parks for commercial energy production should be established there. An important prerequisite is the availability of a high voltage electric grid which can be used for energy transmission to consumers. From this aspect Saaremaa and Hiiumaa are the most suitable. In 1996 the consumption of electricity in Saaremaa (with archipelago) was about 105 GW·h and in Hiiumaa the annual consumption was 42 GW·h. It is expected that in the near future electricity consumption in the West Estonian Archipelago will remain at 150 GW·h per year. Presently electric energy is supplied to these islands through submarine cables from the mainland to Saaremaa and from there to Hiiumaa.

To produce 150 GW·h electricity by wind about 100 wind turbines with rated power of 600 kW are needed in Saaremaa (total investments US$ 56.5 million) and 40 wind turbines with total capacity of 24 MW in Hiiumaa (total investments US$ 22.5 million). However, it would be reasonable to start with the installation of 10 wind turbines with rated power of 600 kW each. Starting with 10 turbines will ensure us price reduction on wind turbines and lower supplementary costs. If seven of these wind turbines are placed on Saaremaa with total power 4.2 MW (investment US$ 3.93 million) they will produce 7203 MW·h electricity per year, which corresponds to 6.9% of the electric energy consumption on the island. The rest three turbines with rated power of 600 kW can be sited on Hiiumaa, having then total installed power in the wind farm 1.8 MW and the need for investments of US$ 1.66 million. The annual energy production is estimated to be 3087 MW·h, which corresponds to 7.4% of electric energy consumption on the island. All together these 10 wind turbines with total power of 6 MW, necessary investments US$ 5.59 million are estimated to produce 10.3 GW·h electricity, which makes up about 7% of the electricity consumption in the archipelago.

7.7 Economic aspects of wind energy

7.7.1 Investments for wind energy

At the present stage the most suitable wind turbines for commercial energy production are those with rated power of 500–600 kW, like for example Danish *Vestas* 44/600. The price of this model is US$ 463,500. Total investments including costs of transportation, basement, transformer, cables, all equipment, training of the operators, five-year free maintenance and two-year warranty service, make up US$ 527,600 per 1 wind turbines. In case of wind farm consisting of 10 turbines the price of 1 wind turbines is US$ 434,500 and the total investments needed US$ 473,800. The power unit will cost US$ 880 per 1 kW for stand alone wind turbines and US$ 790 per 1 kW if 10 turbines are used in a wind park. Experience shows that in complicated conditions constructional supplementary costs may be higher and reach 30% of the price of the wind turbines. In this case the investments per one wind turbines will be US$ 602,760 and in a wind farm US$ 564,800 per turbine. The power unit will cost respectively US$ 1004 per 1 kW for a stand alone turbine and US$ 941 per 1 kW in a wind park.

The installation costs are similar for all types of power plants but the production costs of power plants differ according to the type. The production costs consist of two main groups of expenses:

- capital (investment) costs, which, as a rule, are made by the construction and installation of the power plant;
- running (operating) costs, which are needed continuously for giving production.

For power plants the main running costs are:

- costs of fuels;
- other operating costs like for ordinary repairs and service, salaries of staff, etc.

For wind power plants there is no cost for fuel and modern wind turbines need only little ordinary service. They are highly automated and have good technical durability.

Several manufacturers of wind turbines offer to their production permanent service which contains the ordinary service and repairing or changing all worn-out, failed or broken parts. The service will last 20 years and the annual pay for it is 2.5% of the price of the wind turbines. This makes for annual service per a stand alone 600 kW wind turbines US$ 11,586 per year, in a wind park consisting as a minimum of ten wind turbines the service costs are US$ 10,828 per turbine.

Long term measurements show that at wind speed of 5 m/s (at 10 m height) a wind turbines with rated power of 600 kW produces 1030 MW·h per year, which gives the capacity factor 21.8%. Most Estonian coastal areas have mean annual wind speed 5 m/s or higher, therefore 1030 MW·h is used as the basic value for annual production with a 600 kW turbine.

The average price of wind electricity will be 3.69 US¢/kW·h for stand alone wind turbines and 3.36 US¢/kW·h in a wind park with at least 10 wind turbines. This is the price if the amortisation period counted as nominal 20 years, no profit for investors and no interests on capital (or loans) invested. In complicated conditions where the constructional supplementary costs are higher, the price will be 4.05 US¢/kW·h for stand alone wind turbine and 3.80 US¢/kW·h in a wind park. The running (operating) costs are respectively 1.12 and 1.06 US¢/kW·h.

The price of electricity generated from oil shale, as officially declared by the Price Committee of Oil Shale and Electricity, was 1.52 US¢/kW·h in 1996 and 2.00 US¢/kW·h in 1997. From this

- fuel (oil shale) together with transportation accounted for 1.26 US¢/kW·h,
- service and salaries of employees of power plants 0.74 US¢/kW·h, of which were:

social taxes	0.155 US¢/kW·h
supplies	0.106 US¢/kW·h
services	0.232 US¢/kW·h
depreciation	0.155 US¢/kW·h

The interests on invested capital are not taken into consideration.

Comparisons show that the price of electricity generated by wind is higher than in case of oil shale. However, we must bear in mind that these prices are not fully comparable because initial data and methods of calculation are different. For wind energy the calculated price represents full price including investment (capital) costs and running (operating) costs for the whole operation duration (20 years), i.e. from establishing the wind power plant till its liquidation. The price of oil shale energy includes only running (operating) costs for production, service, repairing and renovation of the power plant.

Comparable are the running (operating) costs of wind energy production (1.06–1.12 US¢/kW·h) and the declared oil shale electricity price (2.00 US¢/kW·h), as the constituents of costs in both are similar.

The comparison of the price of wind and oil shale electricity was made taking into consideration the expenditures in power plants. The cost for high- and low-voltage grid and the losses were not considered. Oil shale power plants are located in North-East Estonia, distances for energy transmission are long and losses high (21.6% from the energy given to the grid in 1996). Wind electricity, as a rule, is used close to the wind turbine and transmission losses are therefore negligible.

The difference in the cost of dismantling wind and other kinds of power plants is substantial, but usually ignored. In the USA for example the dismantling of nuclear power plants is estimated to be as expensive as their establishment (US$ 300–3000 per 1 kW). Additional uncertainties are related to nuclear waste. Wind turbine need replacement after 20 to 30 years, but still the main part of the turbine can be easily recycled and the site taken into use again. Experiences in the USA show that the costs for the dismantling of wind turbines, including removal of foundation and revegetation of soil, do not exceed US$ 30–55 per 1 kW. In case of wind energy there is no accumulation of wastes or exhaust gases or large areas for fuel mining.

7.7.2 Stimulation of wind energy utilisation

Wind energy has become attractive and rapidly developed in countries where renewable energy sources are declared to have priority amongst energy programs and several programs are governmentally subsidised. Development has been based mainly on private funds but governments have created legislative background and assisted by indirect subsidies. In addition to different subsidies on wind energy various special environmental low interest rate loans have been established.

The most common way for subsidies is through the determined selling price per 1 kW·h electricity produced by wind and public payment for the transmission costs. For example in Denmark electric utilities must buy from the private wind turbine owner electricity at 8.41 US¢/kW·h, which makes up 62% of the average consumer price for a Danish low-voltage customer. In Germany governmentally guaranteed price for electricity sold to the main grid is 9.52 US¢/kW·h. In the United Kingdom the price for wind electricity is differentiated by regions. In Scotland with best wind conditions the average price is 5.66 US¢/kW·h, the average for England is 6.14 US¢/kW·h and the lowest price is 4. US¢/kW·h.

Although the price of electricity in Estonia is increasing and the use of wind energy is becoming more cost effective, still investors have to invest US$ 0.55–0.62 million per wind turbine with rated power of 600 kW. Calculations show that at the current price level utilisation of wind energy in Estonia will not give a quick return on assets.

The following calculation was done on (see Table 24) condition that the price of a 600 kW wind turbine is US$ 0.464 million, the rate of supplementary costs is 20% and total investments are US$ 0.557 million.

Table 24 Calculations on utilisation of wind energy in Estonia

Rate of external financing, %	0	0	100	100
Duration of loan, years	-	-	5	10
Interest of loan, %			7.5	7.5
Annual income rate applied by owner, %	7	10	2	2
Price, US¢/kW·h	4.91	6.53	5.54	6.14
Owners' income, US$/year	38970	55680	11136	11136
Payback period, years	5	13	15	17

The most important factors for economic efficiency and profitability of a wind power plant are:

- the source of investment: equity capital guarantees a relatively low price of energy per 1 kW·h and quick payback of investments;
- the income rate applied by owners: high income guarantees better annual income but causes a long payback period of investments;
- the interest rate: high interest rate causes very high price of 1 kW·h and makes payback of investments unfeasible.

In general we can state that presently in Estonia wind energy is more cost effective if wind turbine are based on the owner's equity capital and the income rate applied by the owner does not exceed 6% per year. It is evident that achieving abolition of VAT for wind turbines at least for the starting period will contribute to rapid growth of installed wind power. Also enacting a guaranteed selling price to the grid is important for the development of wind energy.

The easiest way for strengthening wind energy production is to resign from VAT when importing wind turbine. Another important constraint for the development of wind energy is in the present situation the transmission cost (approx. 0.2 US¢/kW·h) which highly determines the consumer price of electricity. Usually wind energy is consumed close to the production place with very small transmission losses and therefore lower transmission costs should be counted for wind energy than presently. However, the reduction of transmission costs is hardly acceptable by electric network owners because of high need for investments to modernise the network. It is more cost effective for the government to reduce VAT and income tax from the production. However, their efficiency in wind energy promotion is less important.

As yet we cannot say anything about the price of wind energy in Estonia, as the only wind turbine at Tahkuna, Hiiumaa, a 150 kW Danish Genvin, has produced electricity only for a few months.

7.8 Case Study: Hiiumaa as a Potential Renewable Energy Island

7.8.1 Island profile

Name of Authority - Hiiumaa County Government, 5 communes. Population 11,800. Area- 1000 km². Length of coastline 325 km. Shortest distance (direct line) to mainland 22 km. Towns with 1000–5000 inh.- 1. Built-up areas with 200–1000 inh. 5. Total number of dwellings 4400. Main natural resources: limestone, clay, curative mud, mineral water, peat, wood, fish, game animals, rich biological diversity. Main economic sectors: fishing, agriculture, food processing, forestry, wood processing, building, handicraft and tourism.

Hiiumaa is situated in the eastern part of the Baltic Sea around 25 km away from the Estonian mainland. The island is formed on a limestone bedrock plain and is covered with glacial, glacio-fluvial, glacio-lacustrine and marine deposits. Amongst the Estonian counties, Hiiumaa is the most forested area and nearly 60% of the island is covered with trees. There are large wetland areas (around 7% of the total area) in the middle of the island. The coastal sea is shallow, there are about 150 small islets around Hiiumaa and large shoals and reefs in more distant areas.

Hiiumaa is part of the West-Estonian Archipelago Biosphere Reserve and is certified by UNESCO as Member of the World Network of Biosphere Reserves since 1990. A national target programme to develop the island as a model region of sustainable development is under preparation (draft law in 1998). According to the adopted Hiiumaa Development Concept, 1993, the development priorities were set as follows:

- to preserve and develop the island as a self-supporting viable development unit;
- to establish an integrated approach to the planning on different levels by using simultaneously ecological, social and economic criteria;
- to revise the principles of land use and resources exploitation and suggest an optional general cross-sectoral framework to develop sustainable nature use (sectors of energy, waste management, agriculture, forestry, tourism etc.).

7.8.2 Ongoing projects and networking in the energy sector

The objective of the funded by PHARE/ECOS-OUVERTURE Programme Round 2 project Energy E.S.T.O.N.I.A. - Energy Efficient Strategies and Technologies of Northern Island Authorities is to transfer the Western partners' know-how and to carry out the general energy plan, to create demonstration projects on energy saving in buildings and installation of a unit with a view to the further establishment of a local advisory agency for energy and environmental management. Also a wind atlas of the island and the surroundings as well as an evaluation of the island's potential to use biomass as fuel for energy production will be prepared. Hiiumaa's partners in this project are Saaremaa (Estonia), Gotland (Sweden), Bornholm (Denmark), Åland (Finland), Shetland and Orkney (both UK).

The project has had the following results:

- provided knowledge about different influences of political and professional levels in energy management. There are no possibilities to compensate inadequate political decisions with the work of specialists. This knowledge is of prime importance by building up a more efficient system of decision-making in the future;
- through study visits and seminars on Gotland, Bornholm and Åland, awareness and understanding about how to manage energy in island conditions in a contemporary, sustainable way and how this can be achieved have improved;
- increased knowledge about tasks and methods to find technical solutions for today's "hot spots" in energy management - for insulation of buildings and pipelines, and for reconstruction of inefficient central heating systems. The results of pilot energy audits, provided by Gotland partners on Hiiumaa, are very useful, instructive and developing;
- examples of Western partners have shown on what level the specialists' knowledge and management skills should be in order to get good results. It must be admitted that specialists are in need of continued education;.
- highlighted the need to pay more attention to a regular basis to education and motivation as means of solving problems of energy management and raising awareness among the general public and also schoolchildren;
- encouraged to start more intensive work with local renewable energy sources such as biomass and wind energy.

Hiiumaa participates in the European Islands Energy and Environment Network ISLENET, funded by the European Commission. ISLENET Work Programme 1998, to be carried out under the SAVE II programme, has been established. The main tasks of this Programme are the establishment of Energy Management Working Groups on islands and the development of on-site training and exchanges between islands. Inter-island working groups will reflect on different stages and different aspects of the development and promotion of sustainable and efficient energy technologies and strategies. The Working Group Themes are as follows:

- Group 1 - Tools for the planners and the decision-makers; The development of energy management policies at local and regional level in islands.
- Group 2 - Tools for raising awareness in energy management.
- Group 3 - The economics of energy efficiency in islands.
- Group 4 - Environmental implications of energy efficiency.
- Group 5 - The implications of EU legislation on energy efficiency policies and measures in islands.
- Group 6 - The elaboration of a Keyfacts database on energy in islands.

In co-operation with Gotland Energy Agency (leading institution) a project to find out and evaluate possible areas on Hiiumaa coastal zone for the establishment of offshore wind farms has been established. Also environmental impacts of offshore wind energy utilisation will be assessed within this project.

7.8.3 Hiiumaa as a Renewable Energy Island

Discussions about the idea to develop Hiiumaa as a Renewable Energy Island (REI) have started. The general objective of this action is to make a switch during the next decade on Hiiumaa Island to using only renewable energy sources. From the aspect of renewable energy sources Hiiumaa has favourable conditions. The relatively long coast line (312 km), many nearby islets and reefs make the island suitable for harnessing wind energy. Large fast growing alder and willow forests are contributing as bases for biomass energy. Also peat and reed can be regarded as energy sources.

There are some initiatives to include the development of Hiiumaa as REI into R&D Programmes and Action Plans, which are under preparation on the national level:

- into Estonian Environmental Action Plan for the next 5–7 years, which is currently under preparation with support from the European Commission's PHARE Programme,
- into National Biosphere Reserve Target Programme (which is currently being prepared for 10 years), as a key issue to achieve for the island the status of a model region of sustainable development.

7.8.4 Pilot wind turbine at Tahkuna

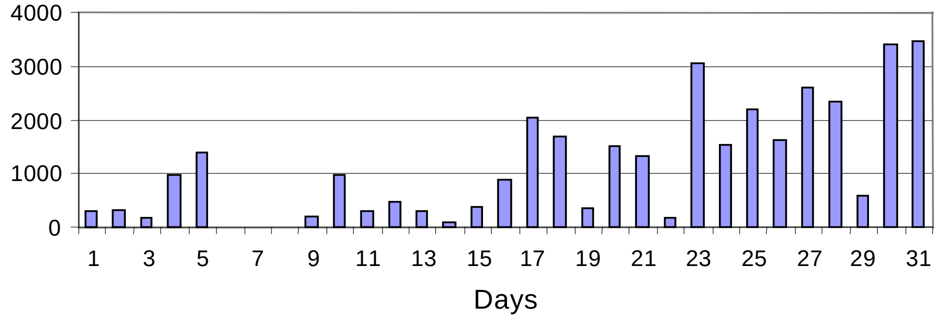
The project to establish on Hiiumaa Estonia's first pilot wind turbine started in 1994 by financing from the Danish Environmental Agency (main sponsor), Estonian Ministry of the Environment and the Estonian Environmental Fund. The project was initiated and hold by the Biosphere Reserve Hiiumaa Centre (recipient institution), the partner was Danish company Genvind. A Genvind 150 kW wind turbine was launched on 19 September 1997 (see operation results in Table 25).

Table 25. General operation results of Tahkuna wind turbine from 19 Sep 1997 up to 31 Jan 1998

Time	**hours**
Total time	2910
Uptime/available time	2333
Generator time	1594
Error time	431
Grid OK time	2908
Production	**kW·h**
September (12 days)	19910
October	21820
November	19940
December	8290
January	35770
February	42710
Total from 19.09.1997 up to 28.04.1998	148440

Taking into consideration the need for frequent inspection and technical work (available time only 79% from the total) in the first months of the turbine operation the production results are noteworthy (see Figure 30).

Figure 30 Production of electricity in Tahkuna by the day in January 1998



8 Conclusions

Generation of electricity causes substantial pollution, being responsible for about one-third of all carbon dioxide emissions and it is a major source of nitrogen oxide and sulphur dioxide. Wind is not an energy source which can cover the main energy production, but it could play a certain role in reducing CO_2 and avoiding the unnecessary use of nonrenewable natural resources. Generating electricity from the wind produces no hazardous by-products and finally when the wind turbine is worn out it can be fully recycled after simple processing.

Estonia's climatological wind resources in areas which do not conflict with other uses are high enough to enable us produce more electricity by wind than 10% of the present consumption. However, the price of wind generated electricity is still high because of high investment costs and therefore its profitability will remain low. There are no subsidies or legislative background to promote the utilisation of wind energy. For these and some other technical and financial reasons only about 3% of energy demand could be covered by wind generated electricity. To fulfil this task siting of wind turbines with total installed capacity of about 120 MW is needed in regions with good wind conditions.

In the present situation there are three different options for wind energy development which all have strictly different character in the sense of investments and reduction of greenhouse gases originating from energy production. The most probable scenarios in the near future are the following:

1. Stand alone wind turbine(s) to cover energy need of certain consumers/enterprise
2. Wind turbine(s) in a local electric network (islands)
3. Wind turbines/wind farms in the main electric network.

The first scenario (1) is most likely the case when no legislative background or governmental subsidies are available. Stand alone wind turbines can produce energy at sufficiently low price level if the internal electric network of an enterprise is used and no transmission costs are present. In this case the enterprise uses in maximal efficiency energy produced by wind and additionally will buy electricity from the main electric network when the wind turbine is not generating sufficient electricity (calm, low wind speed). For the owner the advantage of this system is its high flexibility and autonomous operation from the main energy system. The efficiency of wind turbines can increase also if the produced energy is used and accumulated during the technological process (heating, warming water, refrigeration, etc.). Stand alone wind turbines with an internal electric network may find wider use in fisheries and small harbours, especially in West Estonia, but also on the northern coast of Estonia. The direct cost of electricity generated by an enterprise-owned wind turbine is relatively low as no proceeds are applied, no transmission costs exist and zero or low interest rate investments are used. However, the energy price will be getting much higher if indirect costs are included (alternative use of investments for wind turbine, interests etc.). Moreover, the reduction of greenhouse gases emission of this type of wind energy use is negligible. The reduction in CO_2 emission is small due to the following reasons:

- energy is produced for the enterprise internal use;
- use of wind energy supports energy consuming technological processes but does not decrease significantly energy demand from the main network;
- in coastal regions and harbours energy generated from wind is often replacing energy formerly generated in local small boiler houses by other (lacking) renewable energy resources.

Wind turbines in the local electric network in islands that are not connected to the main electric network have been up to the present the most often discussed scenario (2). Presently electricity is produced on isolated islands by diesel generators. Diesel generators and wind turbines together are well suited for electricity co-production to the same network. However, this is quite an expensive scenario as islands with no connection to the main electrical network are small and few people live there. The local community is not able to buy a wind turbine or pay the high price for electricity itself. Electricity production in small islands can never be profitable and nobody is interested in investing in new power plants as long as governmental subsidies do not make it attractive. Therefore wind turbines can be installed only with state support. The effects of the use of wind energy on islands are mainly a decreased need for expensive diesel fuel and longer durability of the diesel generator as the number of working hours will decrease. The environmental effect of electricity production from wind to replace diesel-generated energy is negligible due to small need for installed power and exhaust gases of diesel engine are less polluting than those from oil shale power plants.

We can argue about the mitigation of greenhouse gases by use of wind energy only if electricity is generated to the main electric network (3). However, differently from the first scenario this is much more dependent on the legislative background (Energy Law, taxation, etc.), subsidies and political decisions but more attractive for investors than scenario (2). Compared to scenario (1) in the present case the electricity cost is higher due to transmission costs (approx. 0.2 US¢/kW·h) and proceeds applied by investors. The advantage of this scenario against the first one is that wind turbines connected to the main electric network can be sited to places with the best wind condition while stand alone wind turbines connected to an internal network are dependent on the location of the enterprise. The most promising area for a main electric network connected wind turbines is the West-Estonian Archipelago, especially the islands of Saaremaa and Hiiumaa, which are the most distant from the large oil shale power plants, whose energy transmission losses are biggest for the islands. Producing electricity from wind contributes to energy saving and reduction of pollutants both by adding additional energy and minimising network losses due to scattered energy production and short distances of transmission. The negative impact of wind energy fluctuation could partly be compensated for by small biomass fired and other small power plants in the same region.

It would be reasonable to start implementing wind energy in Estonia on West-Estonian islands with the best wind-conditions, with a total of 10 units of 600 kW turbines. On Saaremaa the wind park will have 7 wind turbines, total power 4.2 MW, investment US$ 3.93 million, yearly output 7203 MW·h (= 6.9% of the need). On Hiiumaa the wind park will have 3 wind turbines, total power 1.8 MW, investment US$ 1.66 million, yearly output 3087 MW·h (= 7.4% of the need). The two islands together would have 10 WTs, total power 6 MW, investment US$ 5.59 million, yearly output 10.3 GW·h (= about 7% of the islands' need).

If we succeed to produce electricity by wind and to avoid the generation of the same amount of energy from oil shale then we can count with annual reduction of SO_2 emission of about 10–18 g per 1 kW·h and 1350–1400 g CO_2 per 1 kW·h. Table 26 shows the potential decrease of pollutants emission if electricity is produced from wind and two scenarios are compared - the present highly polluting technology and the modern technology expected to be in use after power plant reconstruction.

Table 26 Potential decrease in the emission of pollutants

Pollutant	**Present technology** gram per kW·h	**New technology** gram per kW·h
Sulphur dioxide	10...18	> 0
Nitric oxide	1.1...1.5	1.1...1.5
Carbon dioxide	1350...1400	830
Fly ash	12...20	<0.1

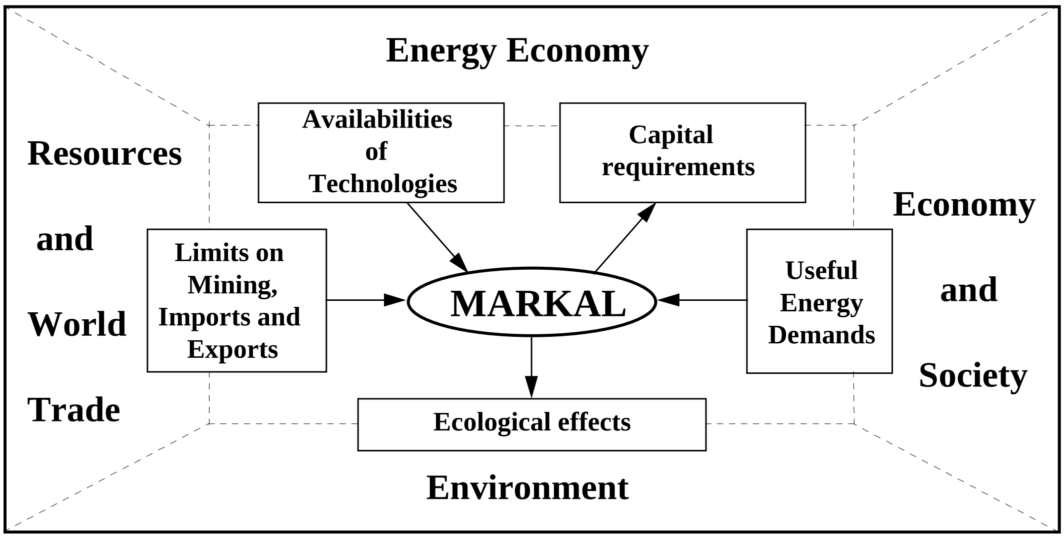
Estonian Energy System and Emissions Modelling Using Markal Model

1 Models used

1.1 Short description of MARKAL model

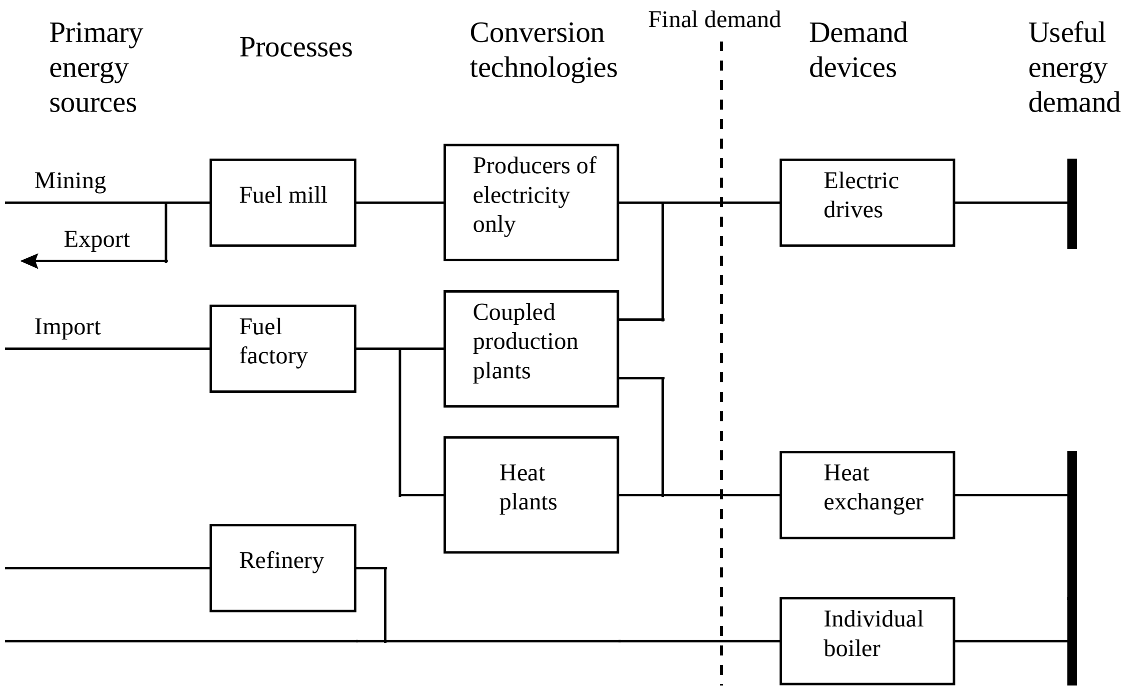
MARKAL (an acronym for "market allocation") is a demand-driven, multi-period linear programming model of the technical energy system that deals even-handedly with supply- and demand-side options. It is a cost-minimising energy-environment system planning model used to investigate mid- and long-term responses to different future technological options, emissions limitations and policy scenarios (Fishbone and Abilock, 1981; Fishbone et al.., 1983; Kram, 1993). MARKAL was developed in the late 1970s jointly at Brookhaven National Laboratory (BNL), USA, and Kernforschungsanlage-Jülich (KFA), Germany, as a part of a collaborative effort of 17 nations under the auspices of the International Energy Agency (IEA). Today the model is in active use in numerous countries all over the world. Its continued development is internationally co-ordinated by IEA Energy Technology Systems Analysis Programme (ETSAP). Figure 31 shows the model interfaces (Fishbone et al., 1983).

Figure 31 Interfaces of the MARKAL model



The MARKAL model optimises a network representation of an energy system depicting entire system from resource extraction through energy transformation and end-use devices to useful energy demand. This network is called Reference Energy System (RES). Each link in the RES is characterised by one or more technologies available to the model. Primary energy sources are converted by supply technologies into energy carriers (e.g. fuels, electricity, heat) that are used by end-use technologies. RES indicates all possible routes from each source of primary energy through various conversion processes to all energy service demands. The flow chart incorporates also the emissions resulting from activities in which energy is converted or transformed. The model creates the best RES for each time period by selecting the set of options that minimises cost (Goldstein, 1994). Very simple picture of energy flows in MARKAL (RES) is presented in the Figure 32.

Figure 32 Energy flows in MARKAL



MARKAL poses a linear programming (LP) problem of the general sort (Fishbone and Abilock, 1981)

$$\min\left(\sum_i c_i X_i\right) \tag{1}$$

subject to

$$\sum_i a_{ji} X_i \leq \geq b_j \quad \text{and} \quad X_i \geq 0 \tag{2}$$

The coefficients c_i for the objective function and a_{ji} and b_j for the constraints are the known parameters; the vectors X_i are the unknown quantities to be found, e.g. the solution of the problem. Here $i = [1, \ldots, T]$ denotes the index of a time period in the total planning time horizon T and j denotes the index of a constraint.

In Estonian applications the objective function has been the total discounted net present cost of the energy system over the whole planning horizon. The objective function can also be a weighted sum of this cost and the environmental emissions or security of energy supply (Kram, 1993).

The variables in a MARKAL model are either exogenous (supplied by the user) or endogenous (determined by the model). Exogenous quantities are, for example, useful energy demands, prices, unit costs (investment, operation and maintenance, etc.) and technical coefficients (lifetime, availability, residual capacity, etc.) of a technology. The endogenous variables, whose values are determined by the linear programming solution, are grouped as follows (Kram, 1993):

- variables representing energy carriers;
- quantity of each energy form available in each period;
- variables related to energy supply technologies;
- new investment in each technology in each time period
- installed capacity of each technology in each period;
- utilised capacity of each technology in each period;
- variables related to the demand technologies.

The heart of MARKAL is the set of equalities and inequalities generated from the parameters supplied by a user. These relationships, called constraints of the model, tie together the variables. The principal constraints are (Fishbone and Abilock, 1981; Kram, 1993):

- satisfaction of demands;
- fuel balances;
- low-temperature heat and electricity balances;
- peak-load and base-load relations;
- limit on operations;
- period-to-period capacity transfer relation;
- cumulative and growth constraints;
- exogenous bounds such as those on market penetration of individual types of technology;
- other constraints such as maximum permissible emissions from the energy system.

After generating from the available parameters the constraint and objective coefficients necessary to describe an energy system, MARKAL produces a matrix of the LP problem.

As a solution of the LP problem MARKAL produces the following outputs for each time period (Kram, 1993):

- capacity expansion or reduction required for a comprehensive set of energy supply technologies;
- level of activity of those technologies selected;
- identification of the end-use technologies that are the most cost-effective;
- an accounting of all energy forms used;
- a marginal value for each energy form;
- a reduced cost for each activity that does not appear at a positive level in the optimal program.

The model will price all energy forms at their marginal cost. It treats interfuel and intertechnology substitution in detail. Costs of emission reductions are internalised in the model.

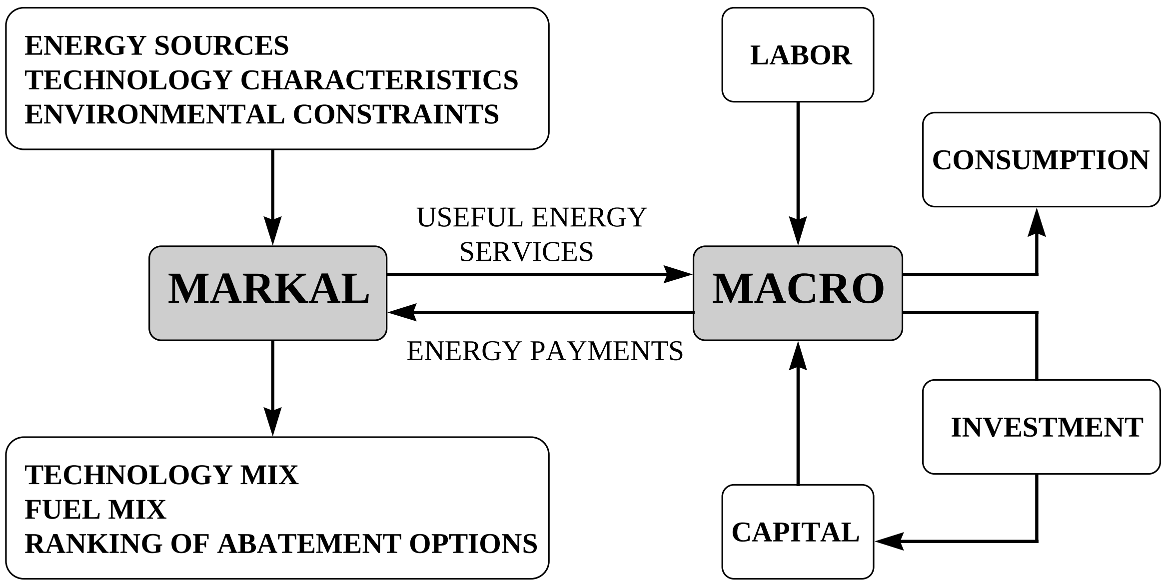
The MARKAL model is used in Estonia only by the Department of Electrical Power Engineering of Tallinn Technical University.

1.2 A short description of MARKAL-MACRO model

To get a good overview of the technological and economic impact on CO_2 reduction, this study uses two models. The MARKAL, a technology market allocation model is confronted with MARKAL-MACRO, a combination of MARKAL with a MACRO economic model.

The MARKAL-MACRO (Manne and Wene, 1992) model was developed to resolve the classical gap between bottom-up (e.g. MARKAL) and top-down (e.g. MACRO) models. The gap is filled by sending the physical flows of energy from MARKAL to MACRO and the energy costs payments from MACRO to MARKAL. A block-scheme of MARKAL-MACRO is presented in Figure 33.

Figure 33 MARKAL-MACRO model



The MACRO is a rather simple model. It uses the concept of one production function (one sector - economic). As MARKAL tends to underestimate end use demand (technical), the MACRO model instead overestimates it (economical).

The MACRO model calculates the gross domestic product and optimises the consumers' total utility balancing the needs for investments and expenditures for energy use.

The advantage of MARKAL-MACRO above MARKAL is that the price effects on energy demand are integrated. Thus the economic implications due to environmental or technology constraints can be estimated.

On the top of the equations of MARKAL, the basic MACRO economic relations introduced in the model are:

1.2.1 *Linkage equation*

The activity of all MARKAL technologies satisfying the demand for useful energy in each of the categories (dm) equals the MACRO demand for the same category, corrected for the -autonomous- "demand decoupling factors" (ddfac). These are set to unity in the start period, for subsequent years they are calculated from -exogenous- annual decoupling rates ($ddf_{dm,t}$) over the numbers of years per period (NYRSPER).

$$\sum_j supply_{dm,t} X_j = ddfac_{dm,t} D_{dm,t}$$

with: $$ddfac_{dm,t+1} = ddfac_{dm,t}\left(1 - ddf_{dm,t}\right)^{NYRSPER}$$

Here $t=1,\ldots,T$ denotes the index of a time period in the total planning time horizon T and j denotes the index of a MARKAL technology.

1.2.2 *Objective function*

The objective function is the discounted sum of the log of consumption (C) over all time periods, with additional emphasis on the last period:

$$UTILITY = \sum_{t=1}^{T-1} \left(udf_t\right)\left(\log C_t\right) + \left(udf_T\right)\left(\log C_T\right) / \left[1 - \left(1 - udr_T\right)^{NYRSPER}\right]$$

with: $$udr_t = \left(kpvs / kgdp\right) - depr - grow_t$$

kpvs initial capital value share,

kgdp initial capital to Gross Domestic Product ratio,

grow potential growth rate,

depr depreciation rate,

and: $$udf_t = \prod_{\tau=1}^{t-1}\left(1 - udr_\tau\right)^{NYRSPER}$$

1.2.3 *Sources of total output*

Total output (Y) arises from the factor inputs capital (K), labour (L) and energy (represented as the weighted sum over all demand categories in MARKAL). Substitution between energy and the capital and labour aggregate is subject to the elasticity (esub). The capital stock is initialised in the start period through the initial capital to GDP ratio (kgdp). Labour input grows at the -exogenous- potential growth rate (grow), scaled to L=1 for the start year.

$$Y_t = \left[akl\left(K_t\right)^{\rho\alpha}\left(L_t\right)^{\rho(1-\alpha)} + \sum_{dm} b_{dm}\left(D_{dm,t}\right)^{\rho}\right]^{1/\rho}$$

with: $\rho = 1 - (1/esub)$

1.2.4 *Uses of total output*

Total output (Y) is spent on consumption (C), investments in capital stock (IV) and energy costs (EC, calculated in MARKAL). GDP is defined as production minus energy cost, or consumption plus investments.

$$Y_t = C_t + IV_t + EC_t$$

and: $$GDP = C_t + IV_t$$

1.2.5 Capital accumulation

The capital stock (K) in each period equals the "surviving" part of the stock in the previous period plus the *average* additions from investments (IV). The capital "survival rate" (srv) is calculated from the depreciation rate (depr).

$$K_{t+1} = srvK_t + (NYRSPER / 2)[srvIV_t + IV_{t+1}]$$

with: $$srv = (1 - depr)^{NYRSPER}$$

Both MARKAL and MACRO are solved under the assumption that there is perfect foresight with respect to changing technologies and economic conditions.

2 General assumptions and data description

2.1 General assumptions

Key assumptions for MARKAL runs were:

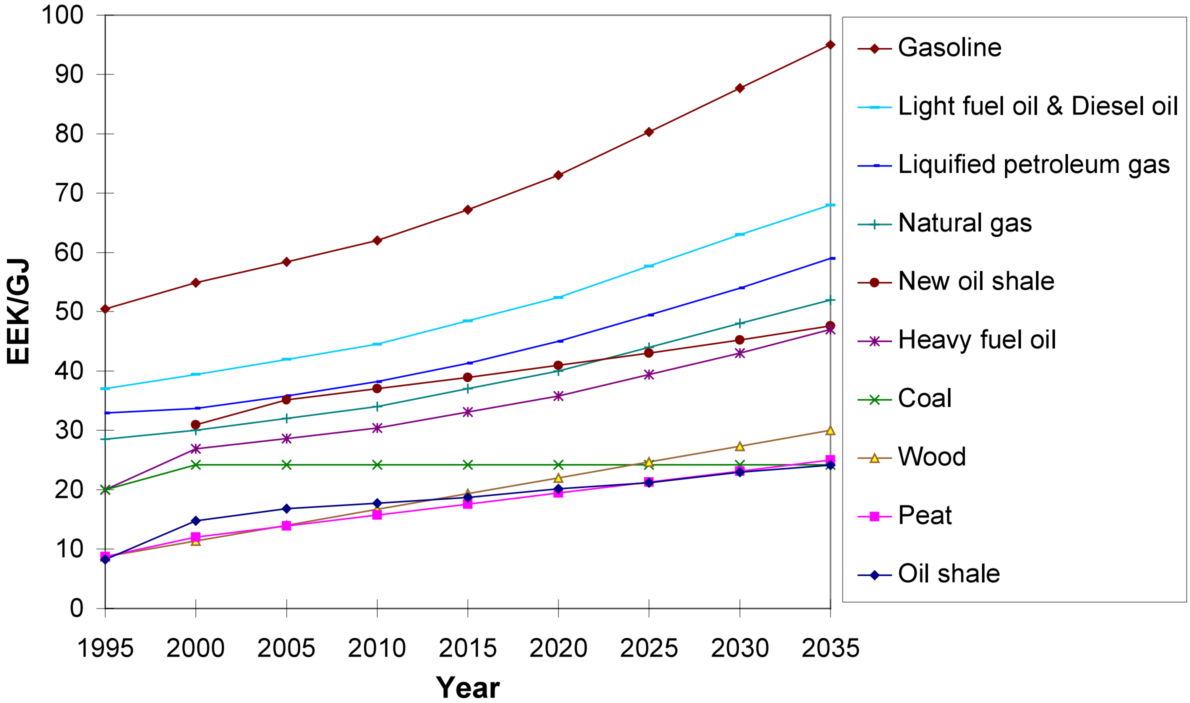
- the base year for the MARKAL calculations is 1995,
- the planning horizon is 40 years, which is divided into 5-year periods,
- Estonian population will decrease from 1.48 million in 1995 to 1.45 million in the year 2000 and to 1.44 million in 2010, after that the population will remain constant,
- long-term annual discount rate is 0.06,
- there are no limits on fuel import and investments,
- electricity import is restricted,
- social and political constraints are not considered,
- Estonia will not be as large an electricity exporter in the future as it was during the 1970s and 1980s,
- so-called "commercial losses" in the electric network will be eliminated gradually during 15 years (presently ca 10% of the production),
- it is assumed that Estonia will implement the existing agreements on emission limitations,
- environmental constraints are accounted as upper bounds on total emissions.

2.2 Fuel price projections

Fuel price projections are of key importance in energy system planning. The tax free price curves of main fuels are depicted in Figure 34.

We use the oil shale price projection made by Prof. E. Reinsalu and Prof. A. Adamson (Tallinn Technical University). Compared with Reinsalu (1996), the price projection of the existing mines and quarries is by ca 10% higher. The cumulative output of the existing mines and quarries is 3675 PJ. The price projection for new oil shale mines (new oil shale) is markedly higher than for the existing ones. It was assumed also that the price of coarse oil shale will reach the level of crushed one in the year 2000.

Figure 34 Tax free price projections of fuels



It was assumed that prices of wood and peat will follow closely the oil shale price. The extraction cost of peat from new fields will be ca three times as high as from the existing ones.

The prices of imported fuels (oil products, natural gas, hard coal) are determined by international market conditions, on which the volumes consumed in Estonia have no influence. Here we use price projections made by ECN (The Netherlands) under EU Phare project Energy Strategy for Estonia. Price forecasts of oil products were made using projections developed recently by international organisations like the IEA and EU (World Energy Outlook, 1996). Drawing on these studies, a gradual growth of crude oil prices from US$/bbl 18 in 1995 to a level of US$$_{95}$ 25 in 2020, and US$$_{95}$ 31 in 2030, is assumed. As there is no refinery in Estonia, oil product prices are derived from the crude oil price using fixed historical ratios. Likewise, the price of natural gas is continuously linked to the oil price. The natural gas price projection made by ECN is in line with projections of Eesti Gaas Ltd (Estonian gas company).

The coal price forecast was also made in line with currently prevailing international projections. The price from 2000 onwards is assumed to remain constant (2 US$$_{95}$/GJ = 50 US$$_{95}$/t) in the EU (Long Term Prospects for Fossil Fuel Prices, 1996).

2.3 Existing technologies and fuel supply options

2.3.1 Power Plants

Today Estonia has no problems with covering its domestic electricity demand as well as import needs of the neighbouring countries. Electricity generation capacity exceeds peak-load ca 1.5 times. The problems of power engineering are the age of the oil shale power plants (23-47 years) and their environmental impact. These plants were designed to supply the North-West region of the USSR not particularly worrying about emissions. During Soviet regime approximately 50% of electricity was exported. In the next 10-15 years the oil shale power plants must be either properly reconstructed or closed.

Data on existing power plants used in the MARKAL model are given in Table 27. For some plants the available residual capacity was taken somewhat lower than the official installed capacity figure is. Hot water boilers installed at the Iru and Kohtla-Järve PP were modelled separately as boiler houses. For modelling reasons the Balti PP was split into three parts: condensing block part, condensing non-block part and non-block CHP part. The blocks at the Iru PP (CHP) were modelled also separately. The shares of industrial backpressure, diesel generators and hydropower are negligibly small. Estonian real hydro potential is less than 1% of the current power generation capacity.

As the electricity generated from oil and gas is more expensive than the oil shale based electricity today, the production of the Iru PP is determined by its thermal load. Mainly, the heat demand is covered by hot water boilers (2×116 MW oil fired and 116 MW gas or oil fired) and therefore the capacity utilisation factor of the Iru CHP blocks is very low. Both turbines of the Iru PP are pass-out ones.

Table 27 Data on Estonian main power plants 1995

Power Plant	**Eesti** PP	**Balti** blocks	**Balti** nonbl.	**Balti** CHP	**K-Järve** CHP	**Ahtme** CHP	**Iru** CHP
Fuel(s)	Shale	Shale	Shale	Shale	Shale	Shale	gas/oil
Lifetime, years	15	10	10	10	10	10	25
Installed (residual) el. capacity, MW	1440	720	460	210	39	20	190
Net efficiency (el., cond. mode), %	29	27	26	20	20	20	40
Fixed O&M cost, EEK/kW	89	102	110	114	150	150	150
Variable O&M cost, EEK/kW·h	0.02	0.019	0.02	0.02	0.025	0.025	0.01
Availability, %	70	70	65	70	70	70	75
Emission factors, g NO_X/kW·he	1.1	1.2	1.2	1.2	2	2	0.6/1.5
Emission factors, g SO_2/kW·he	10,5	13	16.8	16.8	18	18	0/2.3

Data on the existing power plants were updated in parallel under UNEP/GEF project and EU PHARE Programme project on Estonian energy strategy. Data were delivered mainly by Prof. I. Öpik (Estonian Academy of Sciences) and Dr. O. Liik (TTU). Energy Master Plan (1993), Estonian Energy (1995), Operation, Repairs,… (1995) and other sources and informal information from Eesti Energia were used. Mr. M. Landsberg (TTU) participated in the preparation of environmental data.

2.3.2 Boilers

Heat is produced by co-generation plants, thousands of boiler houses of district heating and enterprises and numerous small boilers of households. All big towns and most small towns and villages have district-heating networks and about 70% of apartments are connected with them (Energy Strategy for Estonia, 1997). Today heat production capacity exceeds its demand about three times.

Most Estonian district heating boilers are old. According to the informal information from the heating company Tallinna Soojus Ltd, ca 1% of boilers are less than 5 years old, while 40% are even older than 25 years.

In modelling the existing heat generation capacity, a few larger boiler houses were described separately. The rest of district heating boilers were aggregated on fuel bases. An overview of district heating boilers is presented above (see Chapter 1).

2.3.3 Fuel processing

Fuel processing in Estonia means oil shale liquefaction and production of peat briquettes. There are two crude shale oil production technologies. The Galoter processing technology installed at the Eesti Power Plant uses the same oil shale (crushed) as the power plant (heating value around 8.6 MJ/kg). The Kiviter processing technology uses higher quality enriched (coarse) oil shale with heating value around 12 MJ/kg. Oil shale liquefaction technologies are described in Table 28. In the same table, a possible new liquefaction plant is described as well.

In addition to shale oil production, some part of produced oil is used at the Kiviter Plant to produce oil shale coke for export. Per one energy unit of shale oil spent, 0.5 units of coke and 0.25 units of generator gas are produced.

In 1995, 313,000 tonnes of shale oil was produced and 47% of it was exported (Energy Balance 1995, 1996).

Oil shale processing data were prepared on the basis of information from Prof. I. Öpik (Estonian Academy of Sciences).

The efficiency of peat briquette production is 89% (Energy Balance 1995, 1996).

Table 28 Oil shale liquefaction technologies

Technology	Galoter technol. at Eesti PP	Kiviter technol.	New Kiviter technol
1st Year available			2010
Lifetime, years	20	20	35
Annual production capacity, PJ	15	21	4.5 - 18
Input of energy carriers per unit of activity, PJ/PJ	oil shale - 1	oil shale - 0.964 electricity - 0.01 gas - 0.026	oil shale - 0.9132 electricity - 0.0183 steam - 0.0685
Output of energy carriers per unit of activity	crude oil - 0.64 gener.gas - 0.16	crude oil - 0.53 semicoke - 0.22	crude oil - 0.54 semicoke - 0.22 gener.gas - 0.10
Investment cost, EEK/GJ			40

2.3.4 Energy networks

Data on energy networks were prepared by Mr. M.-R. Esop (TTU and SEI-Tallinn). Electric grids data are based on information from Eesti Energia (Rebane and Vihman, 1995), gas grid data are based on public and informal information from Eesti Gaas and heat grid data mainly on Swedish database. Some heat grid data were updated by Mr. T. Kram (ECN, The Netherlands) according to the Dutch database of ECN under EU PHARE Estonia's energy strategy project. The available information about Estonian heat grids is insufficient or it is not in the form that could be used in MARKAL model. However, one can assume that investment costs of a new heat grid in Estonia are close to the European level.

Electric grids are divided into three parts according to the voltage level:

1. 220-330 kV grid
2. 110 kV grid
3. Up to 40 kV grid

Each grid is described as a subgrid of a higher voltage grid. All demand devices are connected to the low voltage grid, except for the new pulp and paper power plant which is connected to the medium voltage grid. Model data about electricity networks can be found in Table 29.

Table 29 Electric grids

Grid	**Lifetime** years	**Investment cost** EEK/GJ	**Residual value** PJ	**O&M cost** EEK/GJ
220-330 kV	35	50.4	15.6	4.2
110 kV	35	113.5	23.8	9
Up to 40 kV	35	431.5	32.5	18.3

Natural gas grids are divided into four parts:

1. Gas transmission grid (high pressure)
2. Gas distribution grid (households)
3. Gas distribution grid (commercial)
4. Gas distribution grid (industry)

All three distribution grids are connected directly to the transmission grid. Residual value and investments are considered only in the transmission grid. All operation and maintenance costs are assumed to occur in the distribution grids. Model data about gas network are presented in Table 30.

Table 30 Natural gas grids

Grid	**Lifetime** years	**Invest. cost** EEK/GJ	**Residual value** PJ	**O&M cost** EEK/GJ
Gas transmission	50	40.2	70	
Distribution (households)				43.2
Distribution (commercial)				25
Distribution (industry)				3.6

Heat grids are divided into two parts:

1. High density heat grid
2. Low density heat grid

The Tallinn area grid, supplying 40% of the total district heat demand, is the high-density heat grid. Low-density grid is the rest of the country, supplying 60% of the total heat demand. Model data about heat grids are presented in Table 31.

Table 31 Heat grids

Heat grid	Lifetime years	Invest. Cost EEK/GJ	Residual value PJ	O&M cost EEK/GJ
High density	30	579	16	49.7
Low density	30	1150	25	56.8

2.3.5 Fuel Supply Options

Estonian energy sector uses mainly fossil fuels of which a substantial part is imported. Estonian domestic fuels are oil shale, peat and wood. All other fuels are imported, mainly from Russia. The share of domestic fuels in the energy balance is about 64%. Real hydro potential is less than 1% of the present power generation capacity and there are no nuclear reactors. The wind potential is quite remarkable, especially on islands, but there are neither technical nor economical conditions for its large scale harnessing today.

Fuel supply options are modelled in MARKAL in accordance with the data presented in Chapter 1.

2.4 New technology options

MARKAL optimises the technology mix for each time period using data on the already existing and possible new technologies. The attractiveness of a technology is determined by investment cost, lifetime, operation and maintenance cost, cost of energy carriers used (incl. delivery costs), efficiency, availability factor, emission factors and various constraints.

The options for new power plant investments can be found in Table 32.

Information about reconstruction options of oil shale plants was prepared by Prof. I. Öpik (Academy of Sciences). PFBC information was provided also by Mr. L. Kemmer (ABB) and Prof. A. Ots (TTU) (see Chapter 3). For FB units both the oil shale and fuel mix combustion options were modelled (see also Chapter 2).

Data about nuclear and new small hydro plants originate from Swedish database. Wind turbine characteristics base on Dutch data (Ybema et al., 1995). Peat plant data are based on Finnish and Swedish data and on (Energy Master Plan 1993). Small biomass CHP database on Danish experience. Information about other plants corresponds to data of IEA ETSAP programme (Kram, 1994).

New district heating boiler options are listed in Table 33.

New boiler data are based mainly on Swedish MARKAL database used at Chalmers University of Technology, but it is, in average, in the line with real boiler investments during the last few years. All technical boiler data were compiled by Dr. O. Liik and environmental data by Mr. M. Landsberg (TTU).

The use of existing oil shale power plants may become impossible without cleansing equipment in the future due to sulphur emission restrictions. New flue gas desulphurisation technology options are described in Table 34. The data were prepared on the basis of information from Prof. I. Öpik.

All other data on abatement options (NO_x, etc.) were prepared by Mr. M. Landsberg.

Table 32 Options for new power plant investments (incl. reconstruction)[1]

Type	Fuel	Efficiency (% el+heat)	Investment (EEK/kWe)	1st Year Available
Reconstruction with CFB (large)	Shale/mix	34	5300	2000
Reconstruction with CFB (CHP)	Shale/mix	19+39	7750	2000
Reconstruction with PFBC (large)	Shale/mix	44	9200	2005
Reconstruction with PFBC (small)	Shale/mix	44	9200	2000
New PFBC (large)	Shale/mix	43	17800	2010
New PFBC (small)	Shale/mix	43	18500	2010
Coal	Coal	45	15000	2010
Peat CHP	Peat	27+53	21000	2005
Reconstruction with Gas Combined Cycle	Gas	52	5000	2000
Gas Combined Cycle	Gas	55	9000	2005
Gas Turbine (peak)	Gas	30	4000	2005
Gas CC (CHP)	Gas	33+54	10500	2000
Nuclear LWR plant	Nuclear	N.A.	26000	2020
New papermill CHP [2]	Waste	31+44	16800	2010
Small biomass CHP	Biomass	26+58	38000	2005
Hydropower (restoration)	Water	N.A.	10000	1995
Hydropower (new)	Water	N.A.	24650	2005
Wind Turbine (land)	Wind	N.A.	16300	2000
Wind Turbine (sea)	Wind	N.A.	36000	2005

[1] To get the investment estimates in $US\$_{1995}$, exchange rate 1 US$ = EEK 12 should be used

[2] Modelled as a part of possible new pulp and paper industry

Table 33 New district heating boiler options

Boiler	Lifetime years	Efficiency %	Investment EEK/kW	O&M cost EEK/kW	1st year Available
Natural gas	25	89	1800	25	1995
Heavy fuel oil	25	85	1800	25	1995
Coal FB	25	83	4500	200	2000
Peat	25	74	4500	300	1995
Wood	20	69	3500	25	1995
Electricity	25	99	950	19	1995
Light fuel oil	20	85	1000	20	1995
Heat pump	25	(1/0.4)	3000	50	2000

Table 34 New flue gas desulphurisation options

Technology	Lifetime years	Efficiency %	Investment EEK/kW	O&M cost EEK/kW·h	1st year Available
Ahlström scrubber, for one Balti PP block only	10	90	1400	0.0084	1997
Semi-dry FGD for Balti PP blocks	10	85	2200	0.014	1998
Semi-dry FGD for each Eesti PP block separately	15	85	1900	0.014	1998
	15	90	2250	0.011	1998
Semi-dry FGD for two Eesti PP blocks simultaneously	15	85	1660	0.010	1998
Wet Gypsum FGD for two Eesti PP blocks simult.	15	90	1800	0.011	1998

2.5 Emissions constraints

In all scenarios considered, it was assumed that Estonia fulfils targets of international agreements on CO_2, SO_2 and NO_x emissions. Those agreements bind Estonia to reduce its SO_2 emissions by 50% by 1997 and by 80% by 2005 from the 1980 level. The NO_x emissions are not allowed to exceed the 1987 level. According to Kyoto Protocol Estonia's CO_2 emissions between 2008 and 2012 must be at least 8% lower than in 1990.

SO_2 emissions in 1980	275,000 tonnes
NO_X emissions in 1987	70,000 tonnes
CO_2 emissions from the energy system in 1990	37.8 million tonnes

Ministry of the Environment

This means that the following emission limits were applied for all model calculations:

	1995	2005	2010
SO_2	140 kt	55 kt	55 kt
NO_x	70 kt		70 kt
CO_2	37.8 Mt		34.7 Mt

3 Baseline energy demand projection

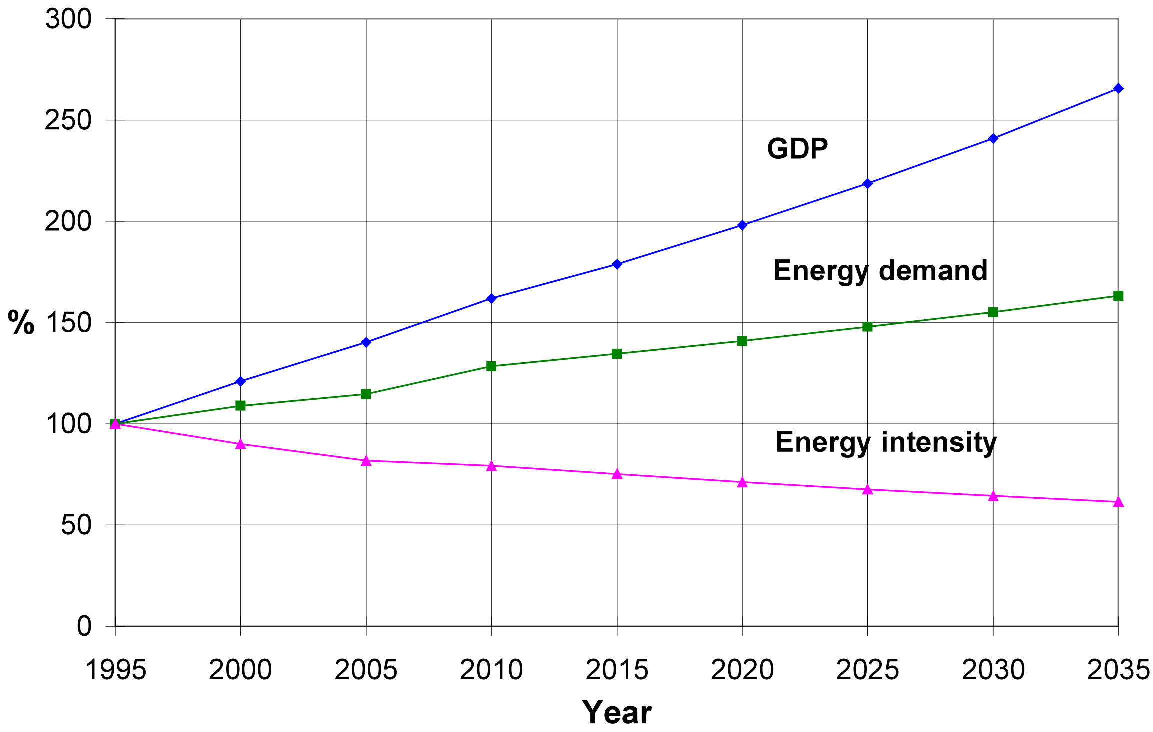
3.1 Economic growth and energy intensity

The development of energy demand is directly related to economic growth. So, the demand projections base on GDP and sectoral economic growth forecasts made by Prof. K. Kilvits (Institute of Estonian Economy) and Prof. A. Purju (TTU) (Purju, 1996).

The scenario with modest economic growth forecast in combination with fulfilment of present environmental agreements was decided to serve as the **baseline scenario** for the current project. The baseline scenario serves as the "non-policy" case in which there are no additional measures implemented to reduce carbon emissions. Even then Estonia can meet the Kyoto Protocol requirements. Reason for this is the fact that in the beginning of 1990's, Estonian energy demand fell due to economic decline and sharp rise in the fuel and energy prices as well as a decrease in electricity exports. It resulted in ca 45% reduction of CO_2 emissions. There should be also a clear understanding that reduction did not happen with no cost. Estonia "paid" for the reduction with the loss of GDP and decline in economy in general (see Chapter 1).

The baseline scenario assumes Estonia's close integration with Western political and economic structures, especially with the EU, but relations with Russia and other CIS (Commonwealth of Independent States) countries are relatively weak. Under this scenario, the GDP is expected to grow on average 2.5% annually during 1995-2035. In developing useful energy demand projections, an average annual energy intensity improvement of 1.4% was assumed. In other words, useful energy demand per capita is expected to grow from 76 MJ/capita in 1995 to 121 MJ/capita in the year 2030. It was assumed that the population number of Estonia will not grow during the whole planning horizon (see Section 2.1). Baseline projections of GDP, useful energy demand and energy intensity are depicted in Figure 35.

Figure 35 Baseline projections of GDP, energy demand and energy intensity



3.2 Principles of making MARKAL demand projections

As MARKAL is a demand-driven "bottom-up" model, a correct and detailed demand forecast is required. Usually, four main demand categories: industry, residential and commercial, transport and non-energy use of fuels are defined. These main categories are, in turn, divided into several sub-categories depending on economic structure and data availability of the country concerned. Breakdown of Estonia's energy consumers is given in Table 35.

As a rule, useful energy demand for each sub-sector should be projected. Depending on the availability of end-use data, it can be quite difficult sometimes, especially for the industrial sector. In case there is no description of demand technologies the final energy consumption must be described instead of useful.

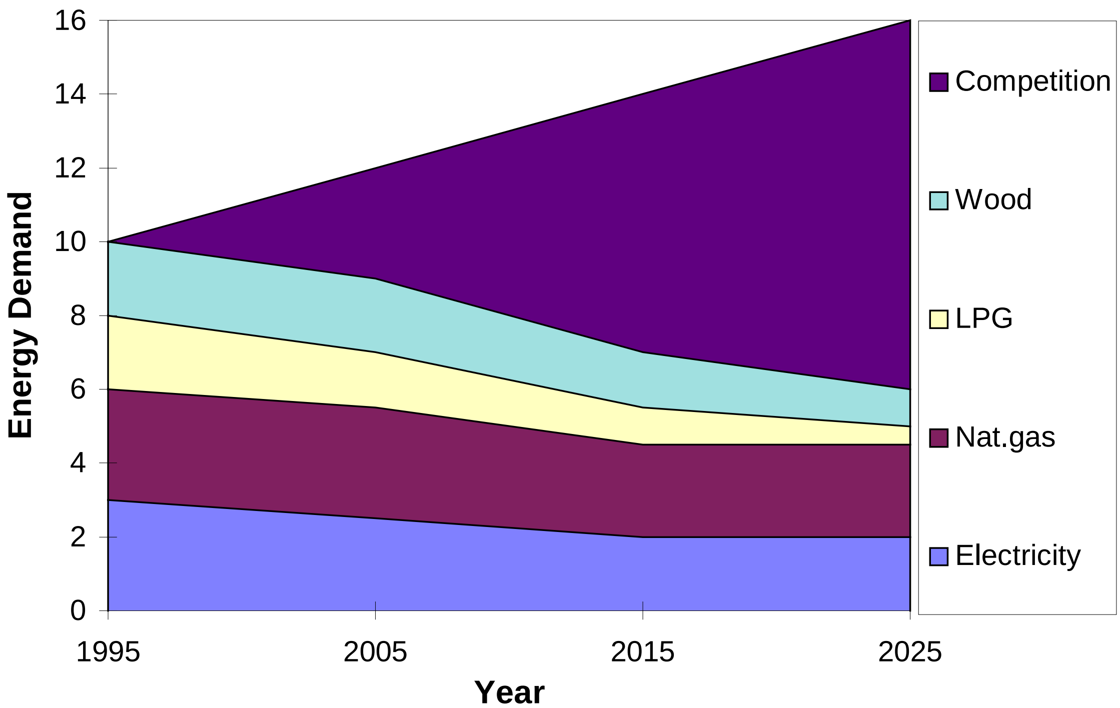
In Estonian case, useful demand projections were made only for residential consumers. For other sectors it was possible to develop only the final energy demand forecasts (for those sectors final demand equals useful).

Table 35 Sectoral breakdown of energy consumers

Industry	Non-energy use of fuels	Residential and Commercial	Transportation
Chemical industry Mechanical industry Textiles and leather Food industry Wood processing Paper and printing New large paper mill Other non-metallic products Fuels and power engineering Other industry Agriculture Construction	Non-energy use of fuels	Spec. el. use in households Space heating in HH Hot water in HH Cooking in HH Lighting in HH Spec. el. use in services Space heating in services	Railways Road transport Private cars Shipping Other transport

MARKAL model needs to allocate shares of demand to the different fuels, including electricity and heat. The choice of fuel per sub-sector and application is determined by the price and lower bounds (non-avoidable consumption) of each energy type and also by characteristics of demand technologies. With time the part of demand not assigned to certain energy carriers (part opened for competition) increases, thus allowing for more significant shifts in market shares. A simple example of making a sub-sector (could be cooking) demand scenario is presented in Figure 36.

Figure 36 Example of making energy demand projection for MARKAL model

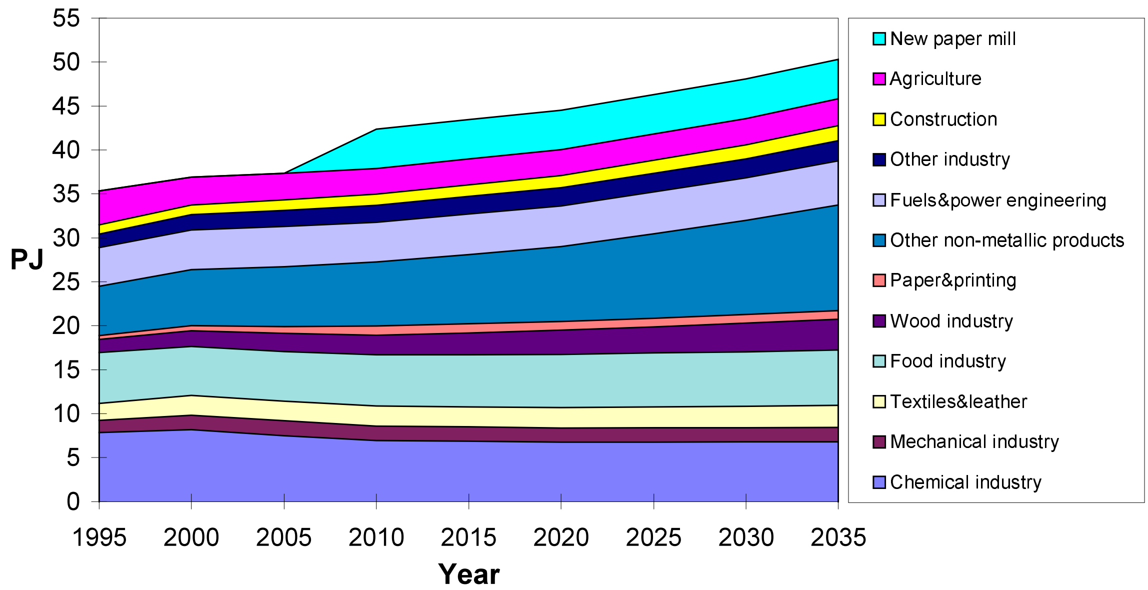


3.3 Baseline sectoral energy demand projections

In the Industry and Agriculture sector, the Total Final Consumption (TFC) projections for sub-sectors were determined as products of 1995 consumption level, macroeconomic volume growth projections and energy intensity improvement assumptions. However, the new pulp and paper plant with assumed production of 250,000 t/yr. was modelled separately.

TFC projections for Industry and Agriculture sector are depicted in Figure 37. Energy demand in Agricultural sub-sector concerns mainly diesel for agricultural equipment, electricity and heat. Biggest industrial consumers in the base year are the Chemical industry, Other non-metallic mineral products, Fuels and power engineering, and the Food industry. Most important changes will occur in the Chemical industry, Other non-metallic products, and in Paper industry.

Figure 37 Total final energy demand projections for Industry and Agriculture sector



For the residential sector, a matrix of final demand per energy carrier for every energy service was composed on the basis of (Energy Balance 1995, 1996). The useful energy demands were derived by assuming efficiencies for every carrier.

For space heating, hot water and cooking useful demand projections are made using forecasts on the number of households and service level per household. Like in the Industry sector, the minimum share of every energy carrier in the useful demand is projected. At that, the part of demand open for competition is zero for the base year, but it increases in time.

The electricity demand for lighting and specific use is projected directly.

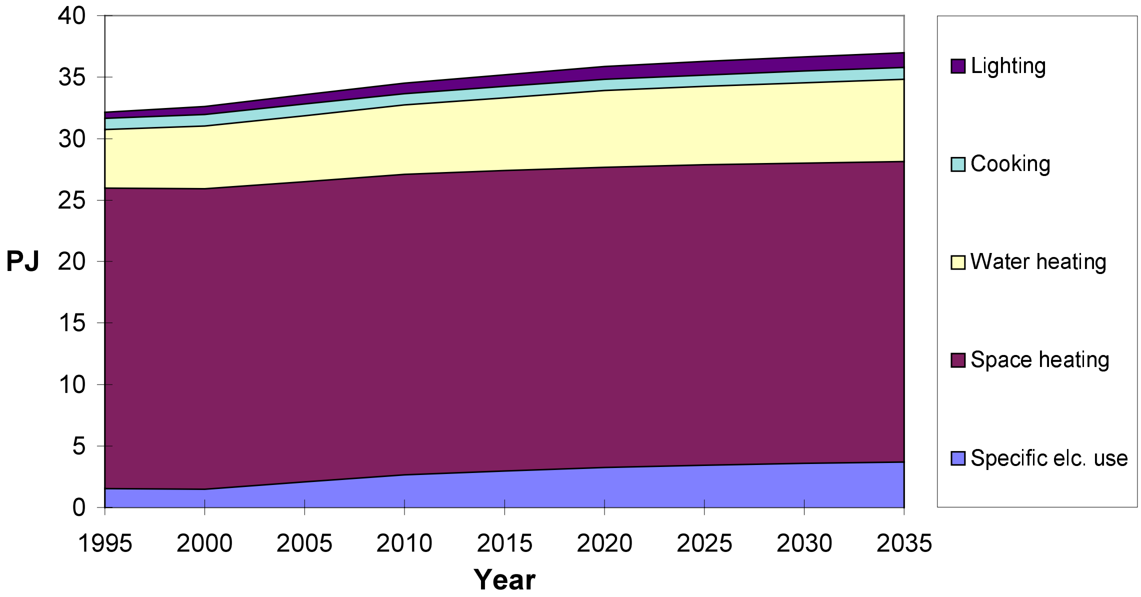
Main assumptions for demand projections in residential sector were:

- Useful demand for space heating will remain constant (population will not grow, more and bigger apartments but better insulation).
- Although a trend to not connect, or even disconnect houses from district heat grids was observed in recent years (inspired among others by tarification systems that favour use of electricity and local boilers over district heating in several places), it is assumed that the decline in district heat use will stop and 70% of households are connected to DH grids and 30% burn their own fuels (firewood, peat briquettes, natural gas, LFO). These shares are not expected to change.

- The useful demand for water heating will increase and reach the Dutch 1995 level in 2015.
- The useful demand for cooking will remain constant.
- Specific electricity consumption will grow from 2.56 GJ/household in 1995 to 5.91 GJ/household in 2030.
- The electricity use for lighting will increase from 0.83 GJ/household in 1995 to 1.91 GJ/household in 2030.

Useful energy demand projections for the residential sector are depicted in Figure 38.

Figure 38 Useful energy demand projections for the Residential sector

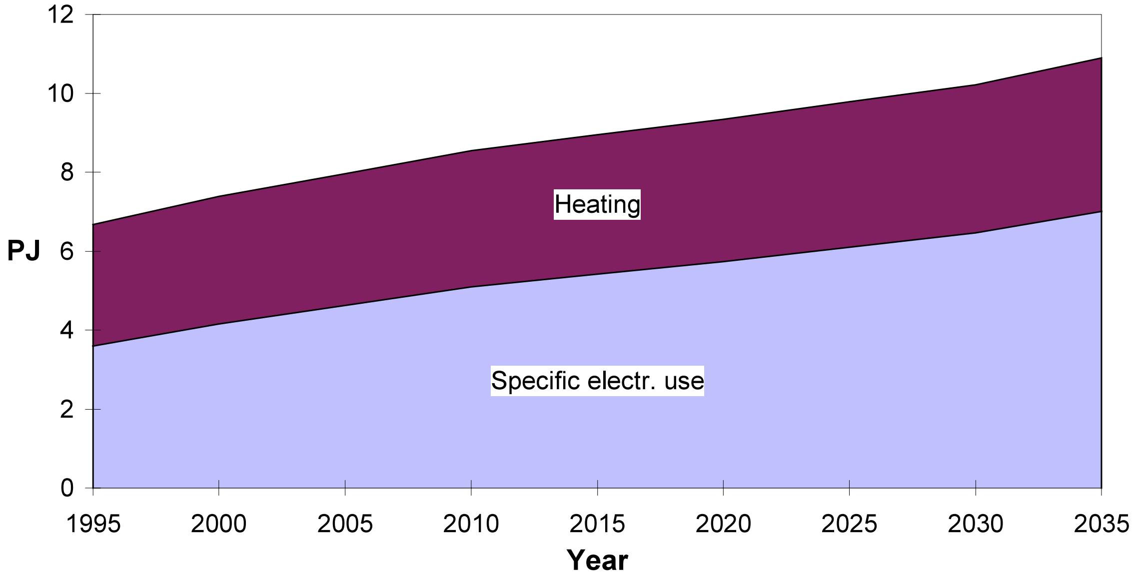


Energy demand in the tertiary sector (services) consists of heating and other electricity use. Electricity can be used for heating as well. Useful demand projections for heating and specific electricity use are based on macroeconomic growth figures for the tertiary sector and energy elasticities of 0.4 and 0.6, respectively. The main part of the growth can be ascribed to electricity.

In the Transport sector, the final energy demand was predicted. The projections base on indicator analysis of transport activities. As sources, (Statistical Yearbook, 1996), (Energy Balance 1995, 1996) and (Mäkelä and Salo, 1994) were used.

<u>Road transport</u> takes into consideration trucks, buses and company cars. It is assumed that buses use only diesel oil, company cars only gasoline, 60% of trucks in 1995 use diesel oil and 40% of trucks gasoline. The total number of trucks is expected to decrease more than twice during 1995-2030, but the annual mileage per truck of diesel trucks will grow almost 5-fold. The mileage of gasoline trucks will remain on the 1995 level. A quick shift to diesel trucks is projected. In 2010, 90% of the trucks will use diesel oil. The annual vehicle kilometres of buses and company cars are expected to grow 21.5% and 80%, respectively, during 1995-2030. The number of buses and company cars will remain constant. Electricity consumption by trams and trolleys in Tallinn is taken into account as well.

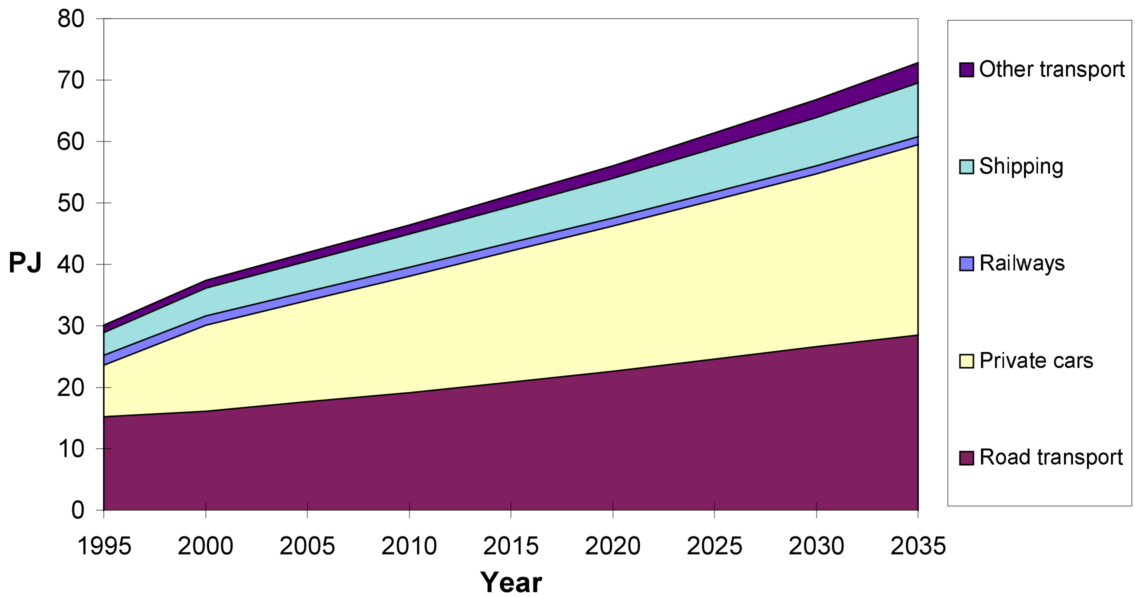
Figure 39 Baseline energy demand projection for Services



The number of private cars is expected to grow from 1 car/4.83 persons in 1995 to 1 car/2.22 persons in 2030. The annual mileage will grow at the same time from 9700 to 15,000 km. Distribution between gasoline and diesel cars will remain unchanged. LPG and electric cars are not considered.

TFC for railways, shipping and other transport (mainly airlines) are projected on the base of volume growth and efficiency improvement estimates. Except railways, proportional development over the different fuels is assumed. A shift from mainly diesel trains towards electric ones is projected.

Figure 40 Baseline energy demand projections for the transport sector



Non-energy use of fuels was presumed to remain on the 1995 level (8.45 PJ).

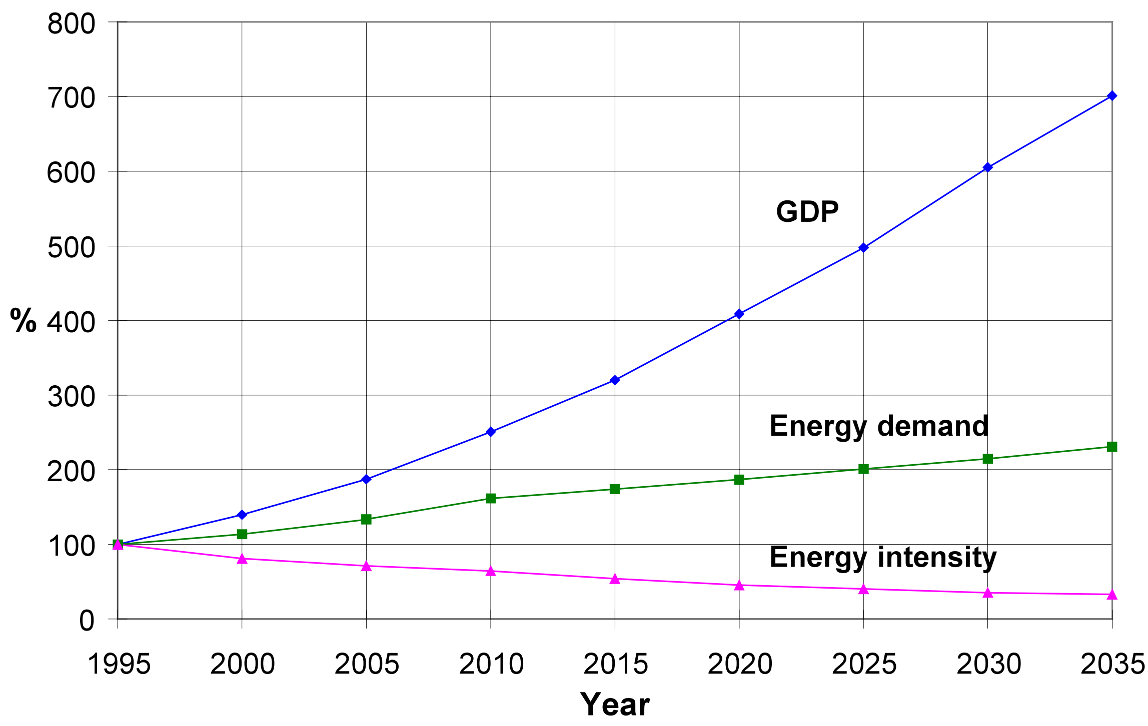
Energy demand projections for Estonia were compiled by O. Liik (TTU), A. Leisalu (ESTIVO Ltd.), H. de Kruijk and M. Motahari (ECN, The Netherlands) (Energy Strategy for Estonia, 1997).

4 High energy demand growth scenario

4.1 Economic growth and energy intensity

This scenario bases on optimistic economic development scenario proposed by Prof. K. Kilvits and Prof. A. Purju (Purju, 1996). Optimistic scenario assumes that Estonia's market is oriented towards both the West and the East and Estonia will become a transit country. Under this scenario, the average annual GDP growth is 5.3%. In developing useful energy demand projections, an average annual energy intensity improvement by 2.9% was assumed. It means that useful energy demand per capita is expected to grow from 76 MJ/capita in 1995 to 168 MJ/capita in the year 2030. High growth projections of GDP, useful energy demand and energy intensity are depicted in Figure 41.

Figure 41 High growth projections of GDP, energy demand and energy intensity



4.2 Sectoral energy demand projections

Energy demand projections for economic sectors under the high growth scenario were elaborated using the same methodology as for the baseline projections. However, the following differences in the assumptions should be pointed out:

- Agricultural demand will be almost the same as for the baseline scenario.
- TFC for all industrial sub-sectors together will increase from 31.1 PJ in 1995 to 55.8 PJ in 2030 (in the baseline scenario 38.9 PJ). Biggest difference from baseline can be noticed in the Chemical industry.
- Only in the high growth scenario a considerable expansion of natural gas based Chemical industry is envisaged. It causes the growth in Non-energy use of fuels from 8.45 PJ to 19.9 PJ during 2000-2010.
- Growing welfare of people will increase energy consumption in the Residential sector and Services and increases also the number of private cars.

- Energy demand in the tertiary sector will be increasing 3.4% annually (1.6% in the baseline scenario).
- Specific electricity consumption will grow from 2.56 GJ/household in 1995 to 8.67 GJ/household in 2030.
- The electricity use for lighting will increase from 0.83 GJ/ household in 1995 to 2.09 GJ/household in 2030.
- The number of private cars is expected to grow from 1 car/4.83 persons in 1995 to 1 car/1.82 persons in 2030 (1 car/2.22 persons in the baseline scenario).
- Rapid economic growth based on transit position of Estonia between West and East will cause also a rapid growth of the transport sector.
- The total number of trucks is expected to decrease by 16% during 1995-2030 (by 57% in the baseline scenario). Average annual increase in total vehicle-kilometres for trucks will be 3.8% (1.9% in baseline).

Demand projections are presented in Figure 42 to Figure 45.

Figure 42 High growth final energy demand projection for Industry and Agriculture

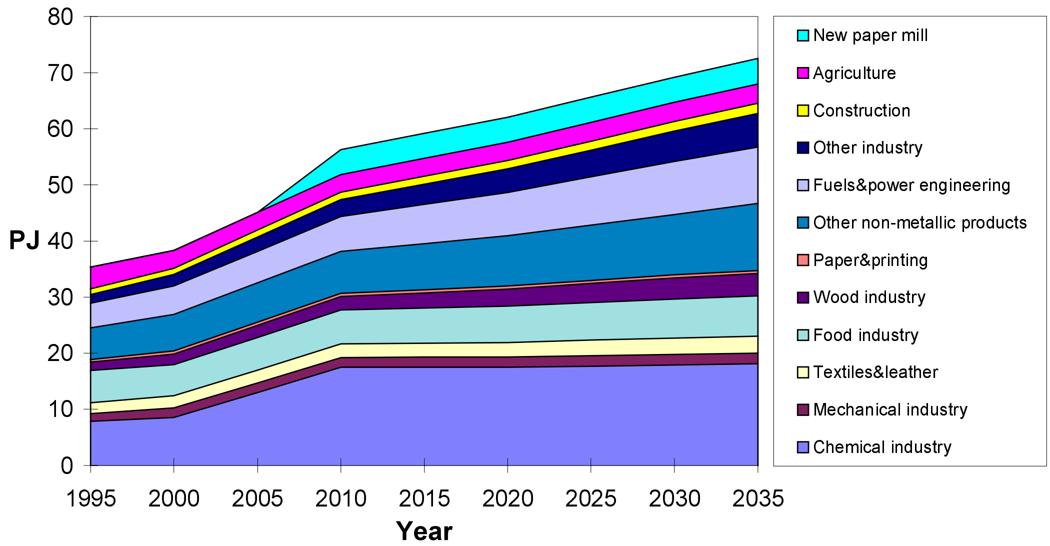


Figure 43 High growth useful energy demand projections for Households

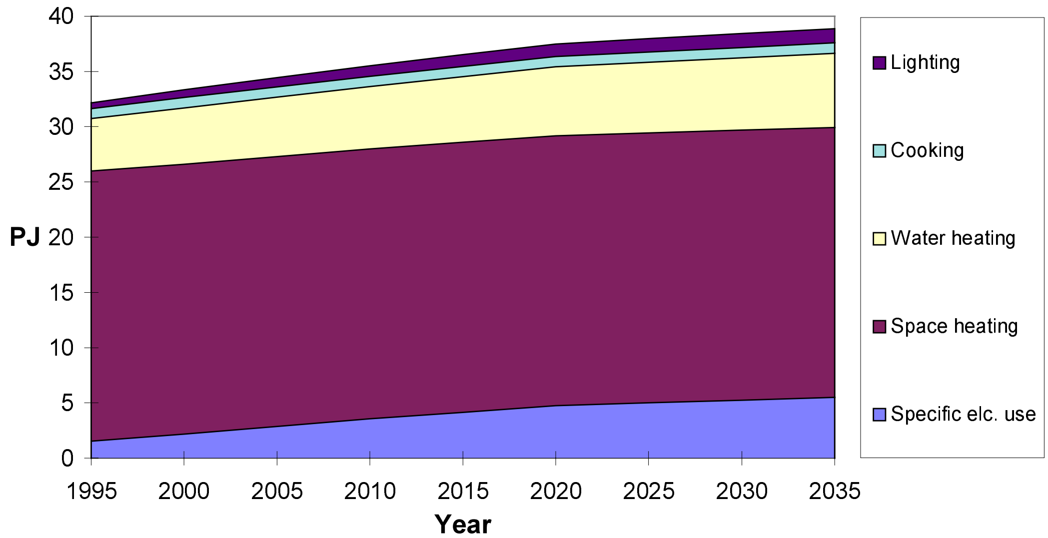


Figure 44 High growth useful energy demand projections for Services

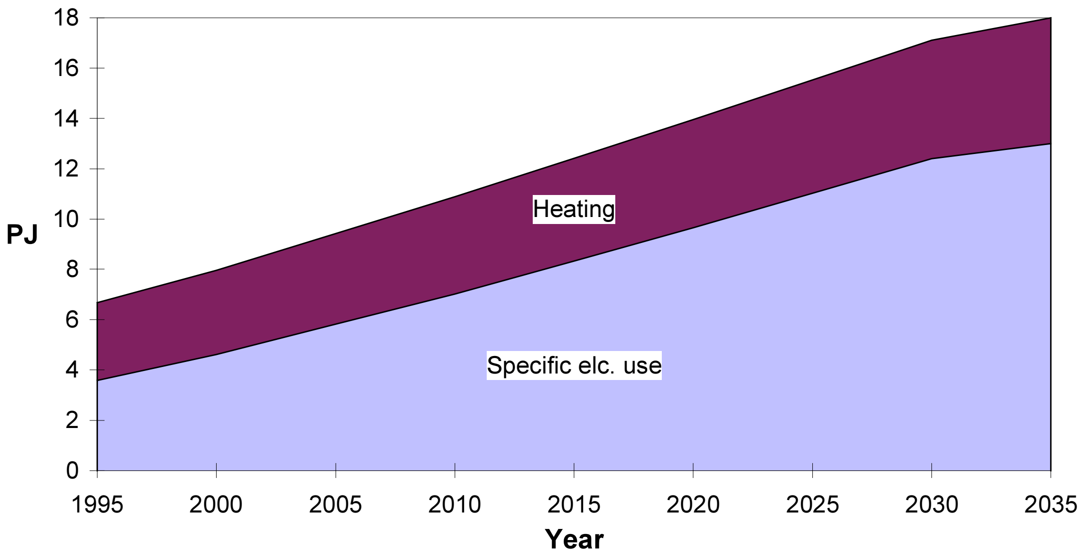
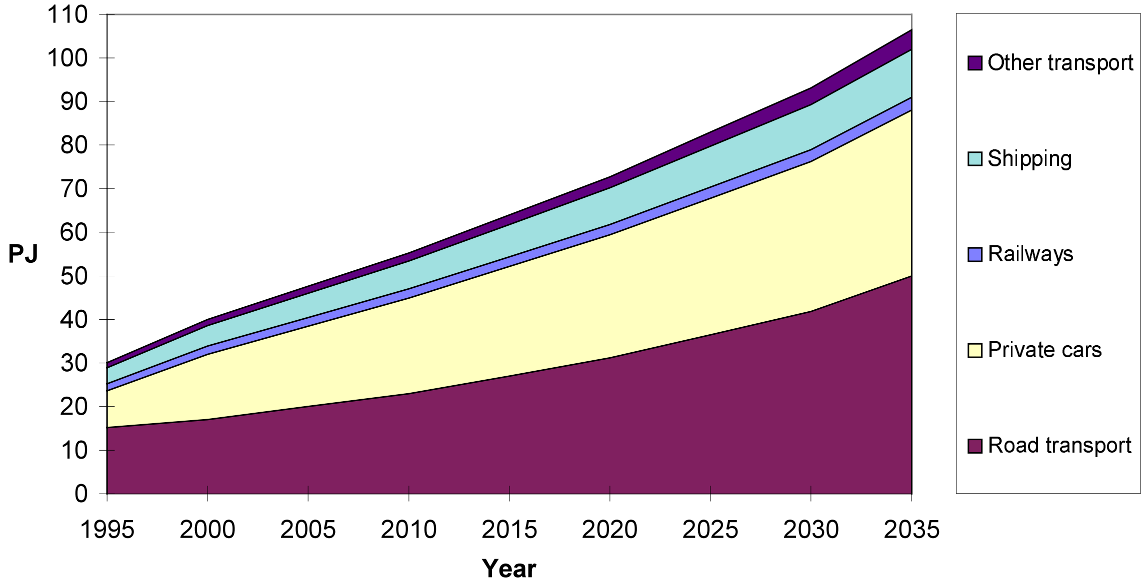


Figure 45 High growth final energy demand projections for the Transport sector



5 Mitigation scenarios and CO_2 reduction options

5.1 Modelling of mitigation scenarios

Considering that MARKAL is an optimising model, already the **baseline scenario is a mitigation scenario compared with the base year situation.** It gives the optimal fuel and technology mix, and resulting emissions that correspond to the baseline assumptions. Moreover, following mitigation options were already taken into account in the baseline scenario in developing energy demand projections:

- Some low-cost heat conservation measures.(see Section 5.2)
- All energy conservation measures in industry and agriculture in the form of decrease of energy intensity of production, see Table 36 (Energy Strategy for Estonia, 1997).
- Reduction of network losses.

Table 36 Annual energy intensity decrease under High Economy Growth(%)

	until 2000	until 2010	until 2020	until 2030
Mining	1.1	1.2	0.7	0.5
Food Industry	0.8	0.5	0.3	0.2
Textile And Clothing Industry	0.8	0.6	0.5	0.4
Leather Industry	1.3	1.4	0.9	0.9
Woodworking Industry	2.0	1.6	1.4	1.2
Paper Industry	2.3	0.7	0.7	0,6
Chemical Industry (Existing)	2.0	3.0	1.2	0.9
Other Non-Metallic Mineral Pr.	0.8	0.7	0.5	0.4
Iron And Steel Industry	1.5	1.7	1.5	1.4
Machinery	1.7	1.7	1.4	1.2
Other Industries	1.5	1.8	1.5	1.4
Energetics	1.1	1.5	1.0	0.9
Construction	0.8	0.6	0.5	0.4
Agriculture	0.8	0.7	0.6	0.6

In reality, the optimal solution can be hardly followed and it can be considered as an energy policy target.

To investigate measures of GHG reduction not considered in the baseline scenario, special mitigation scenarios must be developed. In designing and modelling special mitigation scenarios two different approaches can be used:

1. Economic approach to making changes in general assumptions and cost data (e.g. introduction of environmental taxes, emission constraints, subsidies for some technologies, change of fuel price projections, etc.). In that case the model finds an optimal (least cost) solution under new assumptions and we can find out from results what changes will take place in the energy system. In the guidelines of the project (Technical Guidelines, 1998) this approach is defined as *The Integrated Systems Approach.*
2. Forced introduction of technologies that do not appear in the optimal solution under assumptions made due to their high cost. In Technical Guidelines (1998) this is considered as *The Partial Solution Approach.*

The economic approach can be considered as a "normal" way of MARKAL modelling. The other approach can be used for investigation of economic costs and environmental benefits of certain technological decisions.

Under this project the following mitigation scenarios were considered in the MARKAL modelling:

- <u>Low CO_2 tax case</u> - Scenario with low CO_2 tax (US$ 4/tonne of CO_2 starting from 2005).
- <u>High CO_2 tax case</u> - Scenario with high CO_2 tax (US$ 4/tonne of CO_2 from 2005 and US$ 20/tonne of CO_2 after 2015).

- All high taxes case - Scenario with high CO_2 tax combined with high externalities on SO_2 and NO_X. Here, in addition to previous scenario, the high externalities proposed for the introduction in the EU in the year 2000 (ExternE, Externalities of Energy, 1995) (SO_2 tax US$ 6000/t and NO_X tax US$ 12500/t) were introduced gradually in following manner: NO_X tax increases from US$ 5/t_{NOX} to US$ 5700/t during 1995-2010 and from that level to US$ 12500/t during 2010-2035; SO_2 tax increases from US$ 2/t_{SO2} in 1995 to US$ 400/t in 2010 and to US$ 6000/t in 2035.
- Expensive oil shale case - Scenario with the oil shale price projection rising due to special taxes and increased mining costs over competitive with other fuels level. In principle, this is oil shale phase-out scenario.

All mitigation scenarios were applied to both baseline and high growth demand scenario.

Forced introduction of technologies was used to research consequences of using CO_2 reduction options not considered or the non-cost-effective in baseline scenario (see Section 9).

5.2 Modelling of CO2 reduction options

GHG emissions can be reduced by changes in both supply and consumer sides of the energy system.

Supply side mitigation options for Estonia are:

- Change of fuels, especially reducing the share of oil shale in electricity production.
- New clean and efficient fossil conversion technologies.
- Wider use of renewables (wood, hydro, wind).
- Possible introduction of nuclear power.
- Reduction of grid losses of heat and electricity.

Those options are modelled in MARKAL by describing the technical, cost, availability and environmental data of the corresponding technologies.

The main consumer side mitigation option is energy conservation. MARKAL enables to describe technical conservation measures. In principle, they are treated as additional fuels that satisfy the demand and compete with other energy carriers. Energy saving measures like lower indoor temperature, smaller cars, etc. cannot be modelled directly, they must be considered in developing and analysis of demand scenarios.

In Estonia, the major concern is conservation of heat. Almost 90% of useful energy consumption in the Estonian residential sector goes for space and water heating (see Figure 38 and Figure 43).

In (Strategy for Energy Conservation…, 1996) it is calculated that if all the buildings were fully renovated to the present Estonian standards and if the domestic hot water consumption was in harmony with the present Estonian standards, about 40% of 1995 consumption could be saved. Several demonstration projects still show the conservation potential lower than this ideal figure - in the range of 20-30%.

A long list of 34 technically feasible measures to achieve the energy saving targets is presented in (Strategy for Energy Conservation…, 1996).These measures are grouped as follows:

1. The interventions concerning heat and hot water metering - a prerequisite for any serious energy saving attempt. Without metering the consumption behaviour of people cannot be changed.
2. Low cost investments for improved energy management:
   - Sealing of cracks, gaps, etc. of window glasses and frames;
   - Sealing of cracks, joints, etc. of external doors and their frames;
   - Improvement (repair) of thermal insulation of pipes in basements;
   - Hydraulic balancing of internal heat distribution systems;
   - Installation of programmable DH water temperature controls;
   - Installation of mechanical ventilation and air inlet grilles with manual control;
   - Repair of domestic hot water system (leaking pipes, valves, etc.);
   - Installation of temperature (thermostatic) control valves on radiators.
3. Medium and high cost investments to improve energy efficiency in the houses
   - Adding a third glass to the existing double glazed windows or replacement with new ones with three glasses;
   - Improvement of thermal insulation of external walls;
   - Installation of new insulated sloped roofs or new insulation on flat roofs;
   - Installation of insulation under the ground floor;
   - Installation of independent electric (storage) or gas-fired "through-flow" type water heaters;
   - Improvement of the efficiency of existing boilers, adding automatic controls and making necessary adjustments for fuel switching;
   - Replacement of old inefficient boiler with new and efficient ones;
   - Installation of new thermal substations in buildings;
   - etc.

In MARKAL modelling, it was assumed that energy metering and some low cost conservation interventions (like sealing of cracks) will take place under all scenarios and corresponding outcomes were taken into consideration in developing heat and hot water demand projections. The influence of medium and high cost measures is shown in Section 9.

Electricity is always metered and therefore not wasted by users. "Normal" electricity conservation measures like shift to more efficient industrial equipment, domestic appliances and lighting were considered in MARKAL modelling in making demand projections (see Section 3.2). The main problem in electricity use is minimising "commercial losses" (theft, unpaid bills, etc.). It was assumed in modelling that those presently high losses (ca 10% of net production) will gradually disappear during 1995-2010.

6 MARKAL results of scenarios with baseline energy demand growth

Some most essential results of MARKAL runs under baseline energy demand growth and Base-Case, Low CO_2 tax, High CO_2 tax, All High taxes and Expensive oil shale scenarios are depicted in Figure 46 to Figure 55.

On the basis of model results the following main conclusions can be drawn:

1. Total Primary Energy Requirements (TPER)
   - TPER will first slightly decrease and then grow very modestly due to substantial decoupling between economic output and demands for energy services, reinforced by increasingly efficient energy conversion systems.
   - The share of oil shale will decrease significantly. A higher price and implementation of climate policies pose the most serious threat for oil shale.
   - Imports of oil products (mainly for transport) and natural gas (for CHP plants, DH boilers, industry and residential and commercial use) will rise. Demand for gas will grow as a result of additional environmental actions.
   - Other domestic resources - peat and wood are attractive in most scenarios. Peat use is vulnerable for more ambitious environmental goals. Wood will be an energy source also for a new pulp and paper mill (called Paperwood in figures).

2. Electricity production
   - Under base case conditions oil shale based power production will continue to be the major electricity supplier through reconstructed units of existing power plants.
   - Reconstruction of part of conventional oil shale power plants to CFB combustion is a robust option appearing in all scenarios examined. Reconstruction of other existing units to PFBC and especially building new FB plants appear less attractive.
   - Amount of natural gas power (CHP, condensing combined cycle and gas turbines to meet the peak requirements) will increase significantly.
   - Gas fired CHP units offer the best prospects for combined heat and power production in all scenarios considered. Peat fired CHP is favoured in scenarios without CO_2 tax.
   - On the long term, coal and nuclear power plants offer the best prospects to replace oil shale electricity generation. Nuclear power is favoured only when the highest environmental standards are considered.
   - Except for the own production of electricity and steam from black liquor in the newly built paper mill, nonfossil power production (hydro, wind) will remain negligible.

3. Heat production
   - In the base year the total district heat production is dominated by boilers, both large ones feeding extensive distribution grids and smaller ones feeding local systems.
   - Total heat demand will decrease ca 10% during 1995-2000 and then will remain at an almost constant level.

- The share of boilers in total production is expected to decline.
- Natural gas fired CHP units are the strongly preferred option for larger district heating systems and the use of wood boilers will expand for smaller schemes.
- On longer term peat CHP looks attractive also, but it appears to be vulnerable to charging of high SO_2, NO_X externalities and CO_2 taxes.
- Natural gas is favoured also in fuel choice for individual boilers, where available.

4. Energy costs

- Energy system costs comprise all the costs made in the energy system: import and domestic fuel costs, production costs (capital, operation and maintenance costs), transport and distribution costs. Tax revenues are treated separately. Although they constitute a cost for energy consumers, they are not "real" cost on the macro-economic level.
- Despite the fast energy intensity improvements, total costs of the energy sector rise faster than TPER. This is on the one hand due to rising prices for domestic and foreign energy supplies and on the other hand to capital required for new investments. Consequently energy prices will have to rise.
- Required investments only in power plants until 2015 are some 13 billion EEK_{1995} (about 1 billion US$). Current tariffs appear insufficient to build up financial reserves for this purpose.
- Expenditures on fuels will shift from domestic to imported flows. This trend will be stronger when more rigid environmental policies are applied.
- Total energy system cost constituted ca 25% of the GDP in 1995, which is a typical level for economies in transition. Under baseline economy development the Total System Cost/GDP ratio will decrease only to 20% at the end of the planning period.
- High energy system costs are affected by the current low level of per capita GDP, high energy intensity of GDP and high needs for heating due to cold climate combined with poor quality of buildings and district heating systems.

5. Emissions

- New technologies, economically viable under base case conditions, help to ensure that sulphur and carbon emissions fall below agreed targets. This means that the baseline development that considers only SO_2 and NO_X restrictions and where no special actions to reduce CO_2 are taken, is already a GHG mitigation scenario.
- The CO_2 tax levels tested affect strongly the relative competitiveness of power and heat generation and other energy options. CO_2 emissions could fall well below the base-case level.
- Increasing environmental problem will be NO_X emissions from the transport sector.

Figure 46 Baseline primary fuel supply

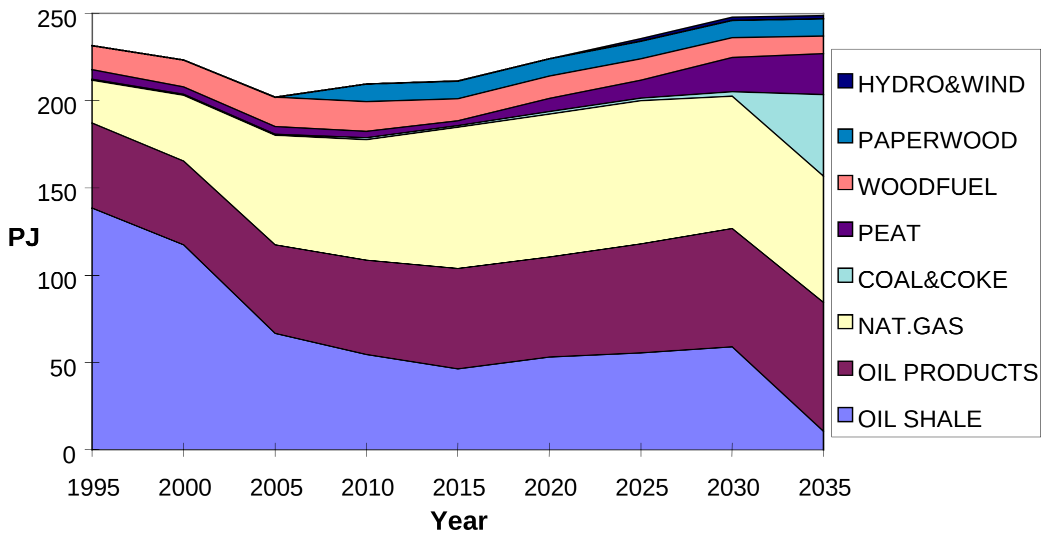


Figure 47 Primary fuel supply under Low CO_2 Tax + Baseline Demand scenario

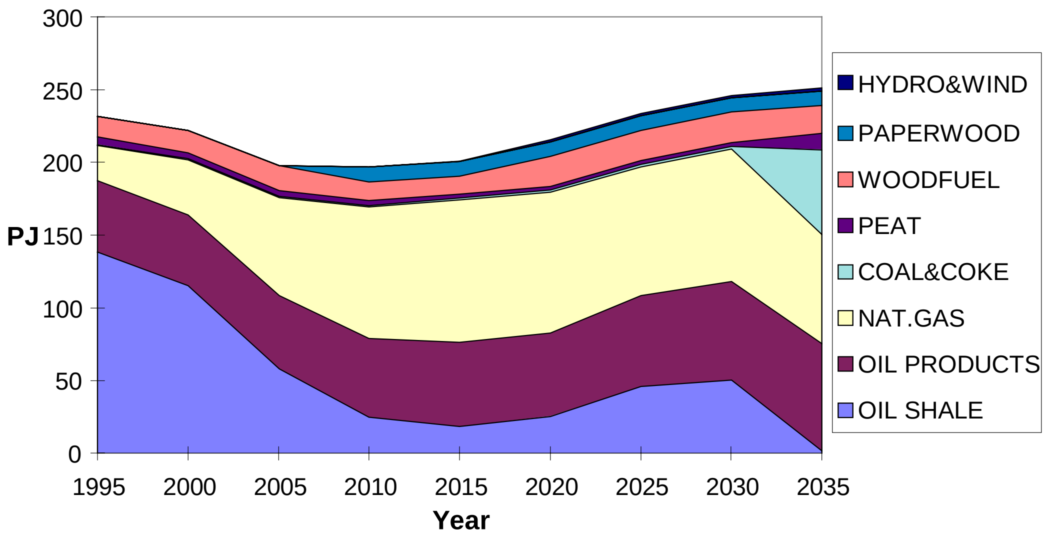


Figure 48 Primary fuel supply under High CO_2 Tax + Baseline Demand scenario

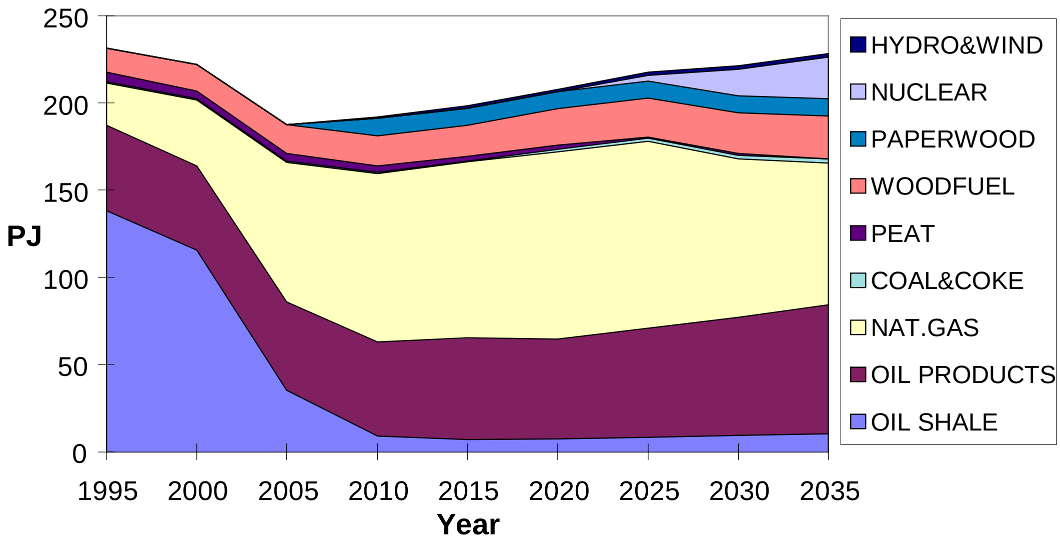


Figure 49 Primary fuel supply under All High Taxes + Baseline Demand scenario

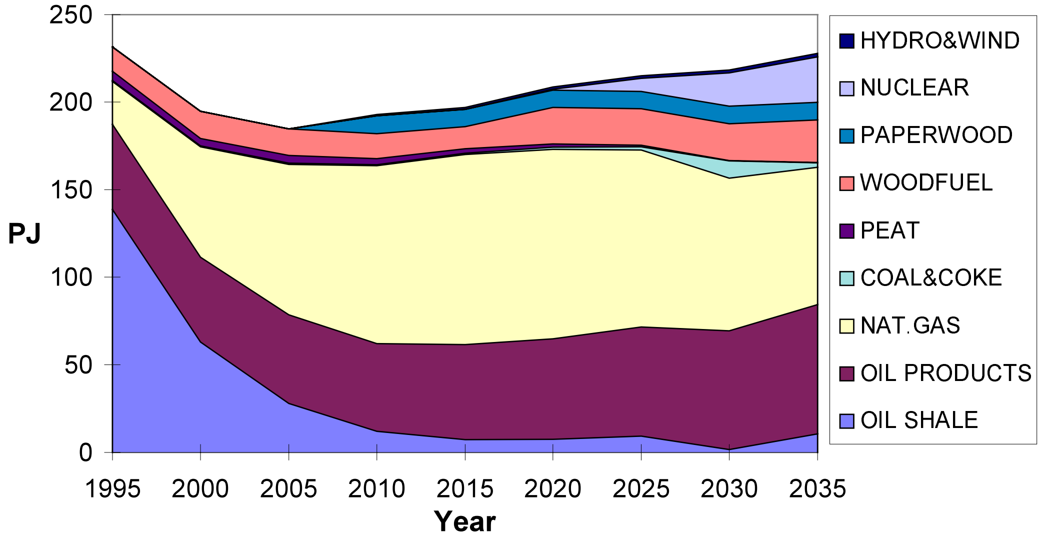


Figure 50 Primary fuel supply under Expensive Oil Shale + Baseline Demand scenario

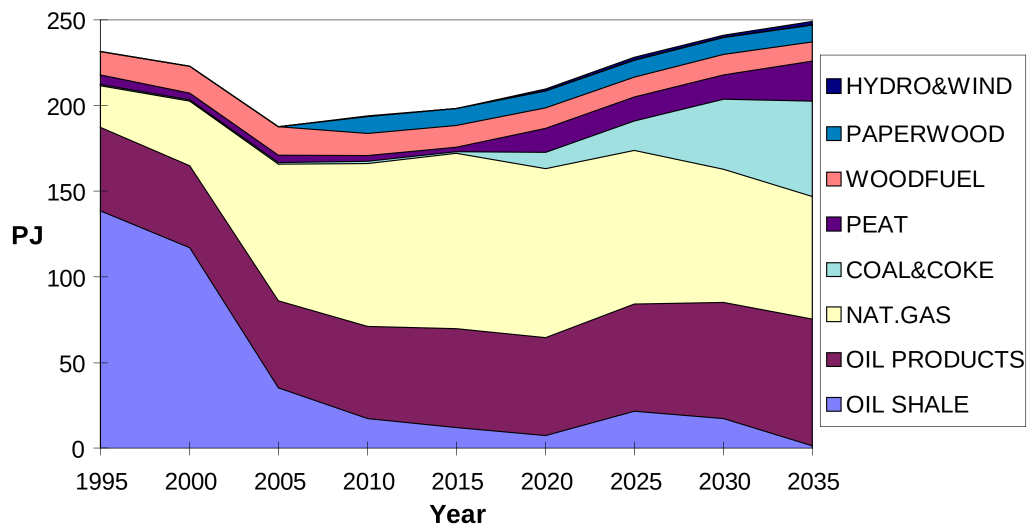


Figure 51 Baseline electricity production by fuels

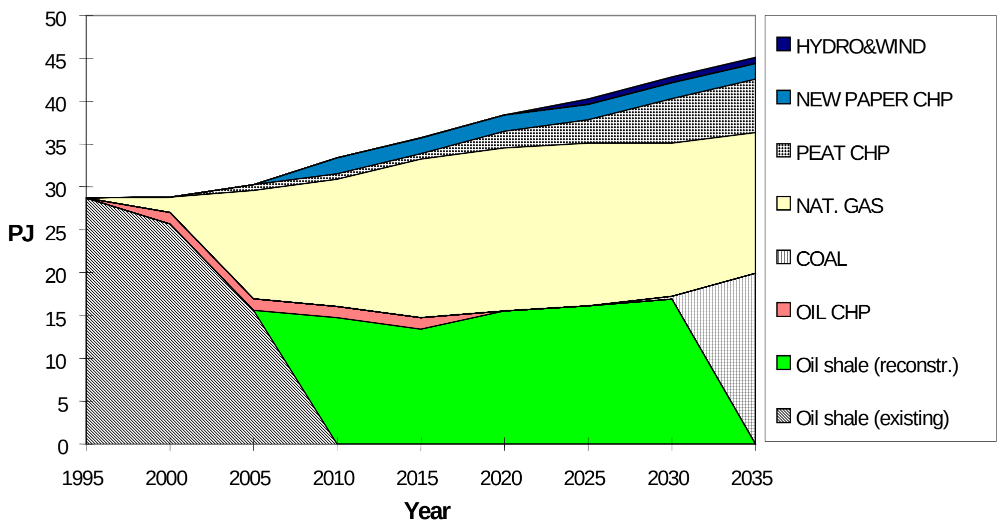


Figure 52 Electricity production under All High Taxes + Baseline Demand scenario

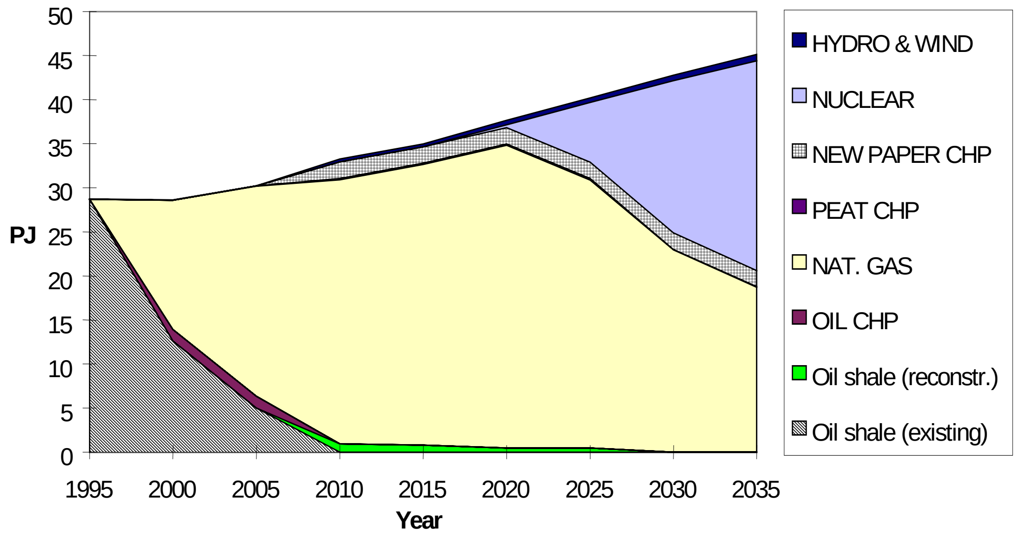


Figure 53 Development of Total Energy System Cost/GDP ratio (Baseline Demand)

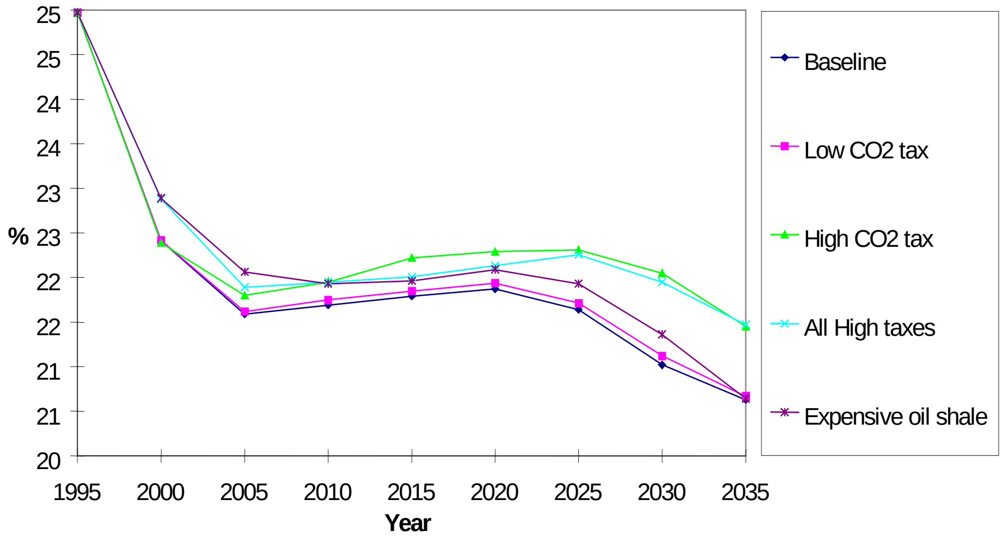


Figure 54 Total CO_2 emissions from energy system under baseline energy demand

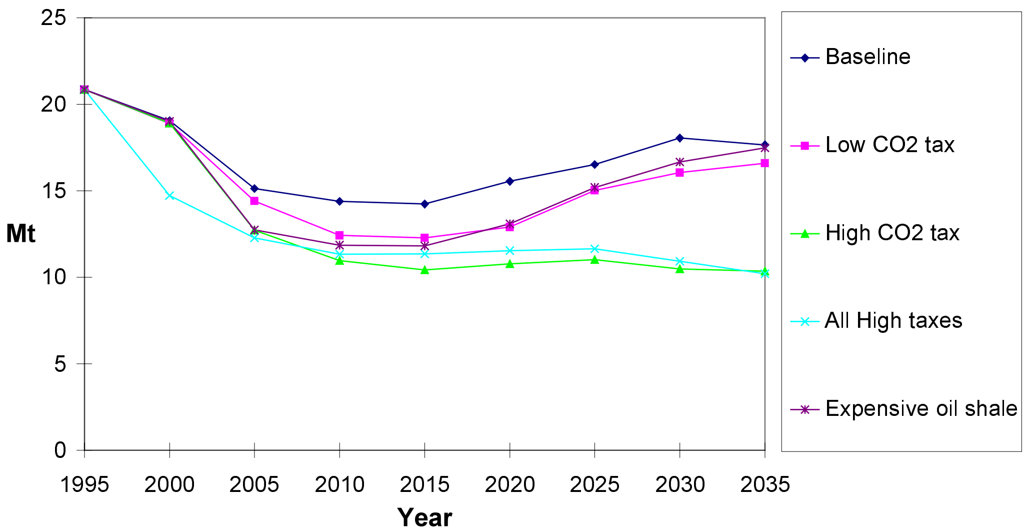
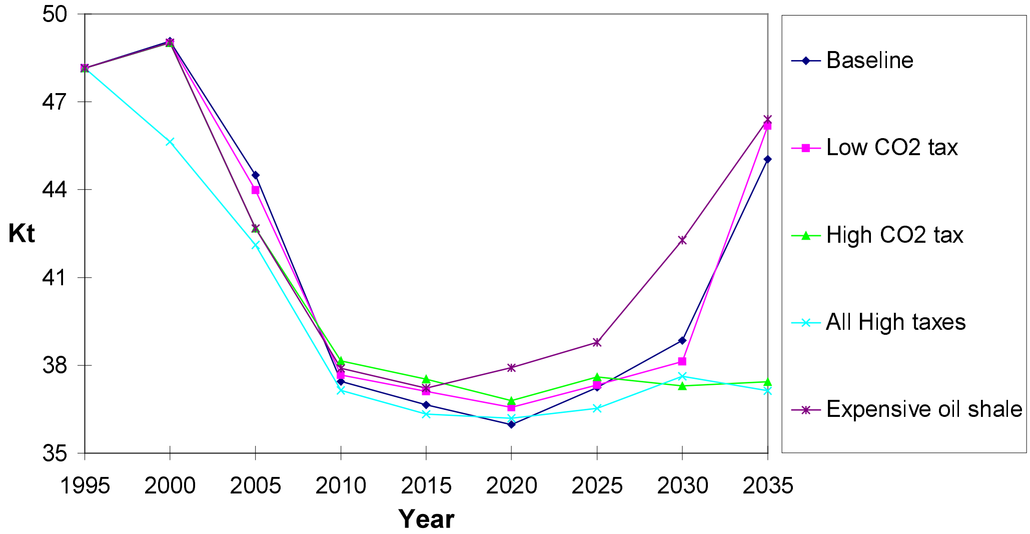


Figure 55 Total NO_X emissions from the energy system under baseline energy demand



7 MARKAL results of scenarios with high energy demand growth

Most important results of MARKAL runs under high energy demand growth and Base-Case, Low CO_2 tax, High CO_2 tax, All High taxes and Expensive oil shale scenarios are depicted in Figure 56 to Figure 65.

Most of the comments and conclusions made on the results of analysis of the scenarios with baseline energy demand growth (see previous chapter) are valid here also. In the case of high energy demand growth only the following different findings can be pointed out:

1. TPER will remain almost stable until 2005 and will increase then ca 60% during the next 30 years. Shifts in fuel use will be similar to scenarios with baseline demand.
2. In electricity production, assumptions on operation and maintenance costs of PFBC installations were changed according to the discussions in Energy Strategy for Estonia (1997) and also this project. Here O&M costs of PFBC units were lowered ca 30% compared with calculations under baseline energy demand. This change makes CFBC and PFBC reconstruction of existing oil shale power stations equally attractive already under the base-case scenario and PFBC technology is preferred under high environmental taxes.
3. District heat demand will decrease during 1995-2000 by ca 10%, but will rise after that slowly.
4. Total energy system cost will decrease from 25% of GDP in 1995 to 11-12% in 2035. Cost differences between scenarios are rather small. Old worn-out technologies must be replaced in the near future anyway and costs of new technologies used by the model in the considered scenarios are quite similar. Here investments of EEK 16-18 billion into power plants will be required until 2015.
5. CO_2 emission will increase over the 1995 level in the long run, except under high CO_2 tax. The emissions will still stay well below the Kyoto Agreement

target (34.7 Mt). Increasing NO_X emissions mainly from transport, but also from increasing natural gas consumption will be a serious problem under fast development of economy.

Figure 56 Base-case primary fuel supply under high energy demand growth

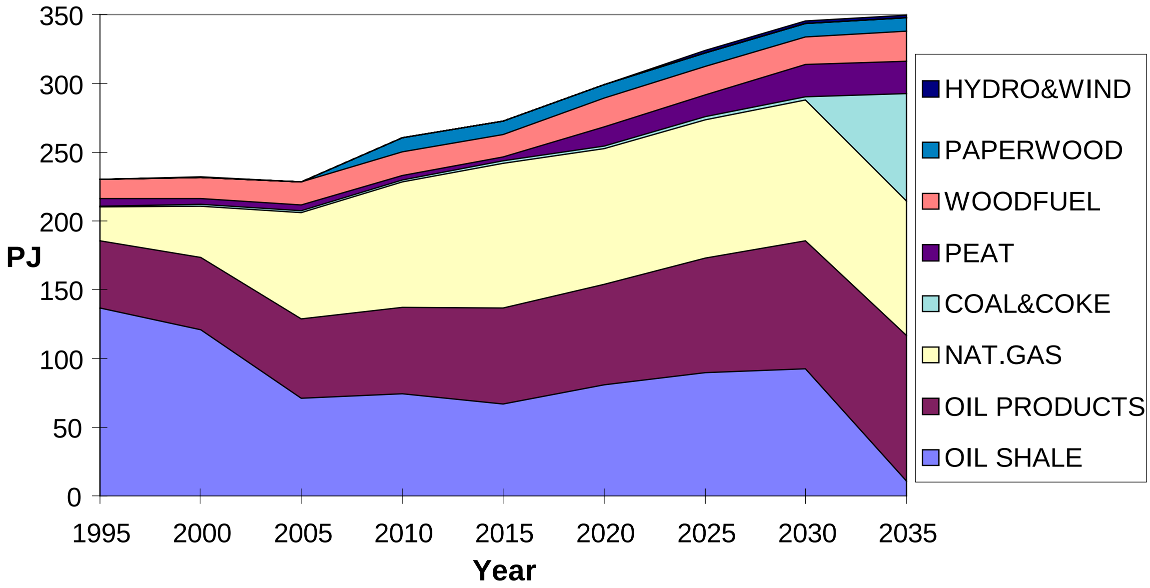


Figure 57 Primary fuel supply under Low CO_2 Tax + High Demand scenario

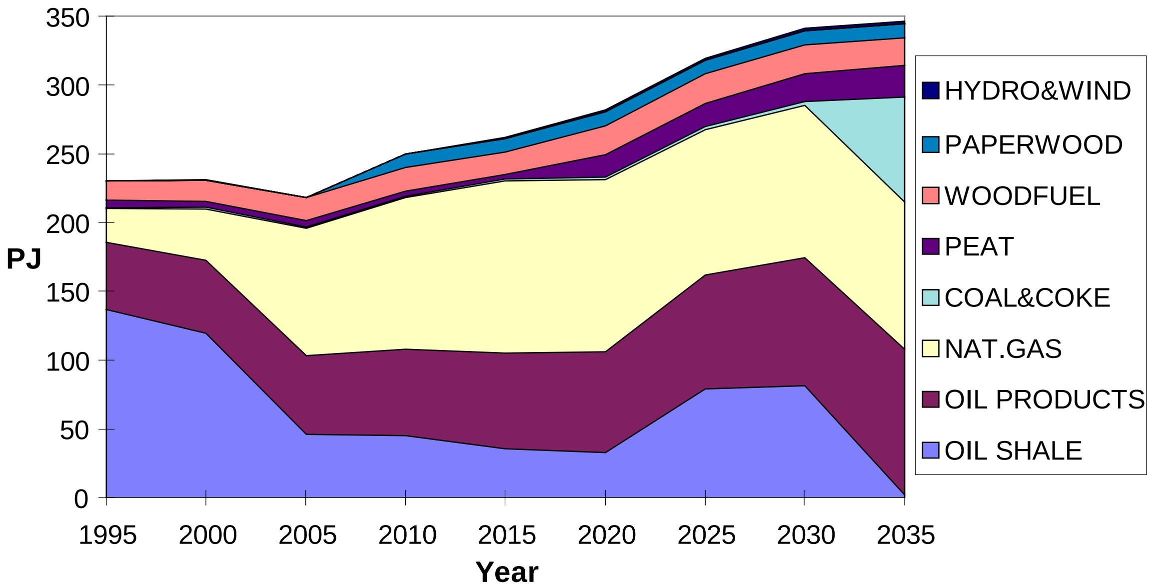


Figure 58 Primary fuel supply under High CO_2 Tax + High Demand scenario

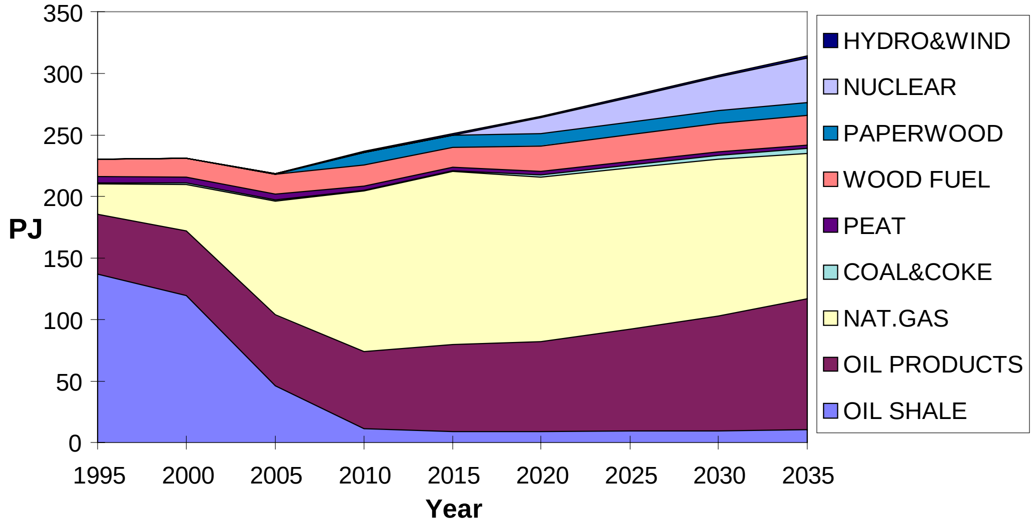


Figure 59 Primary fuel supply under All High Taxes + High Demand scenario

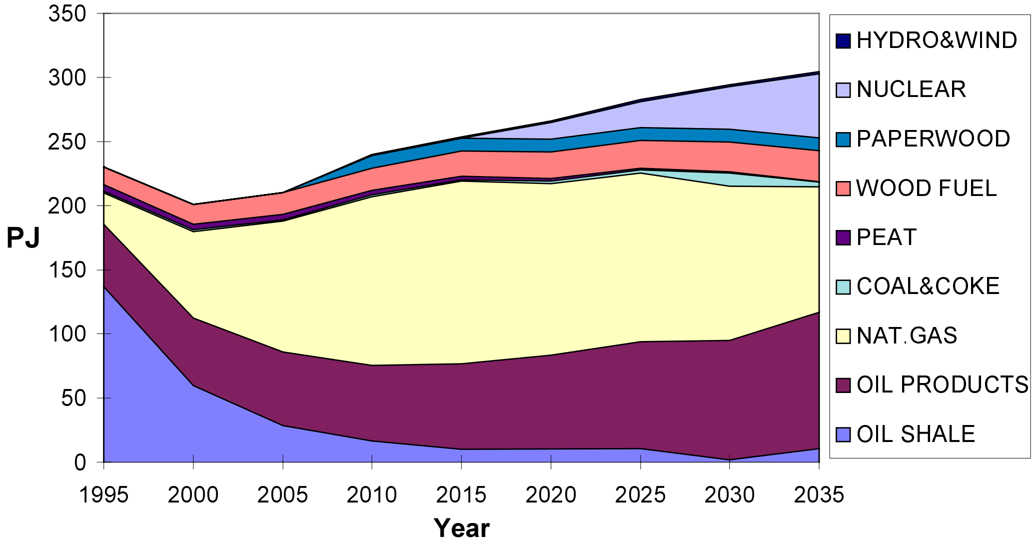


Figure 60 Primary fuel supply under Expensive Oil Shale + High Demand scenario

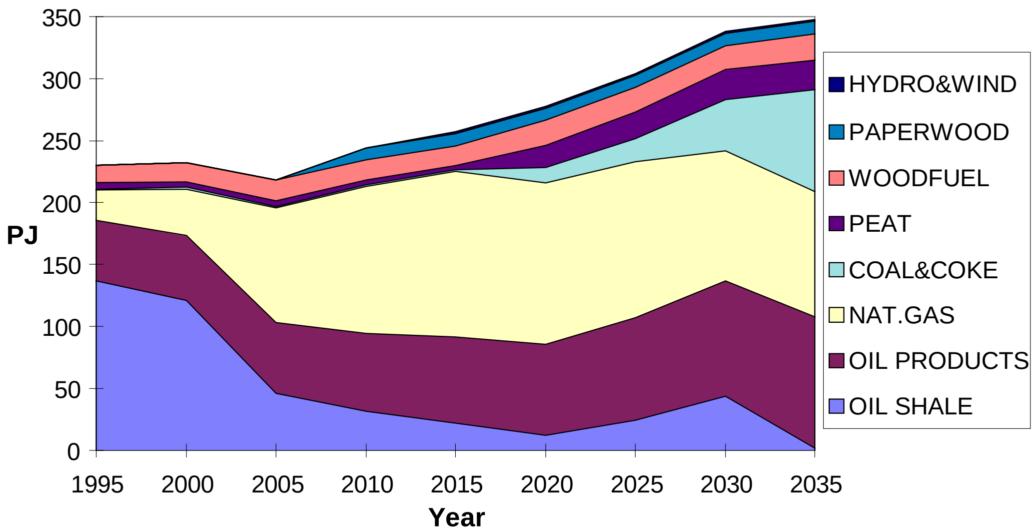


Figure 61 Base-case electricity production under high energy demand growth

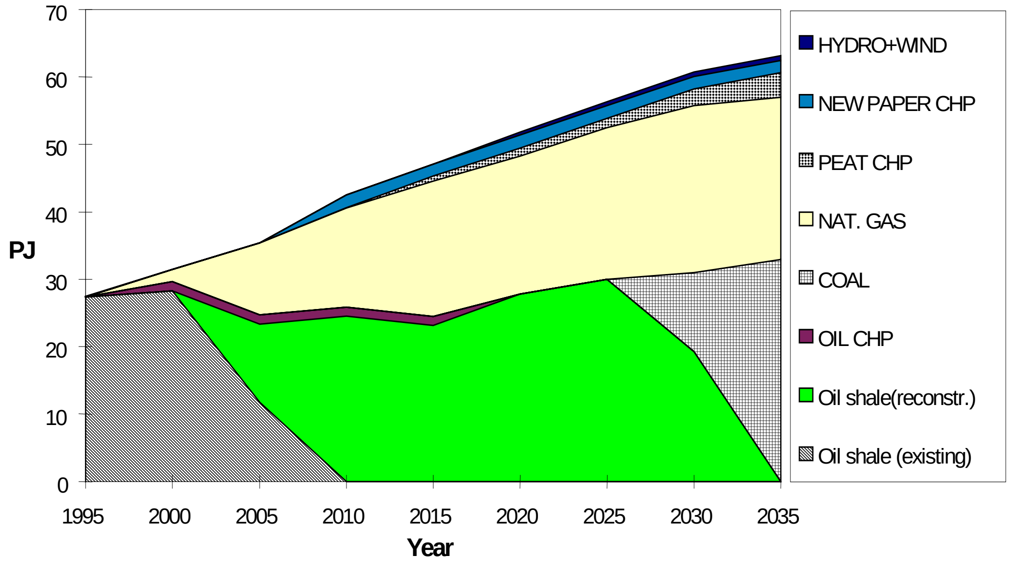


Figure 62 Electricity production under High CO_2 Tax + High Demand scenario

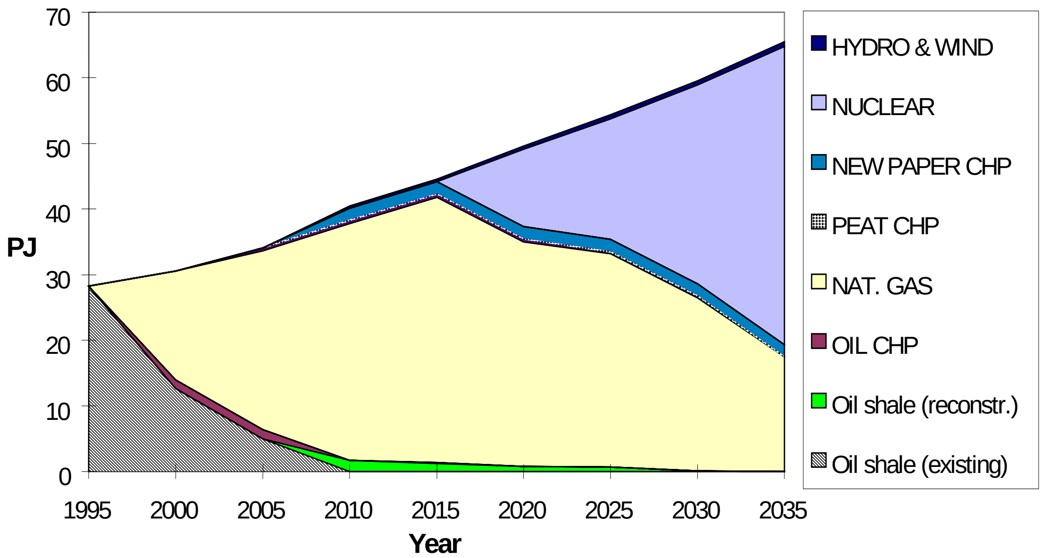


Figure 63 Development of Total Energy System Cost/GDP ratio (High Energy Demand)

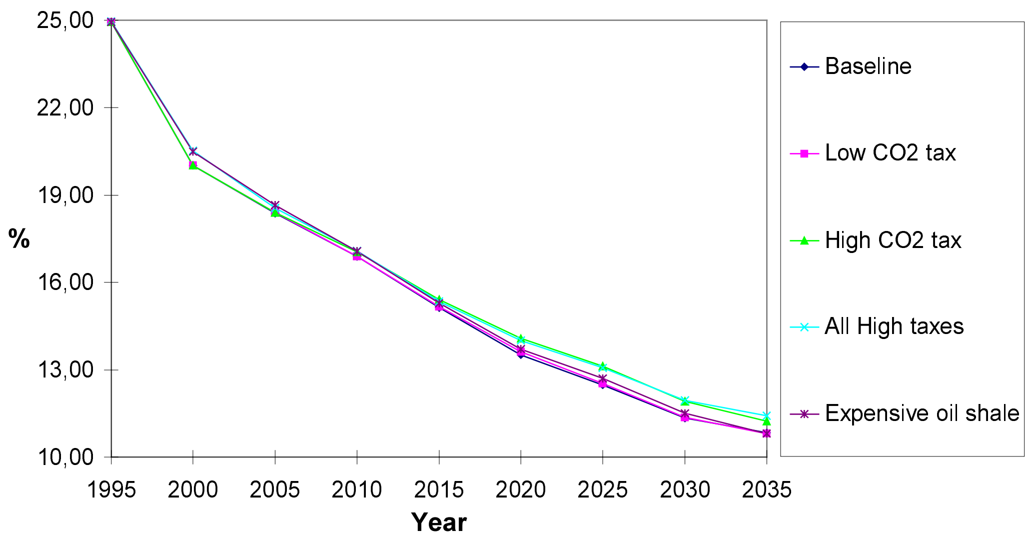


Figure 64 Total CO_2 emissions from the energy system under high energy demand

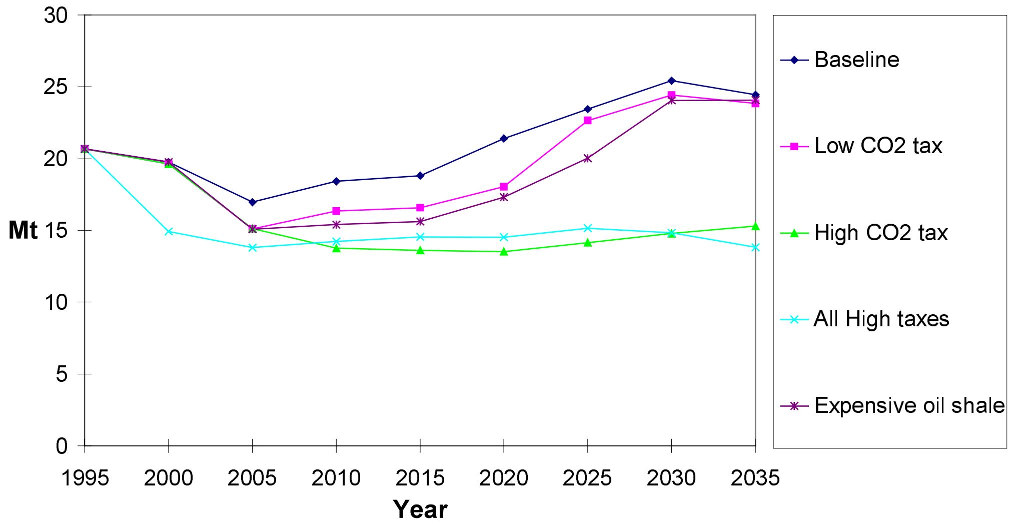
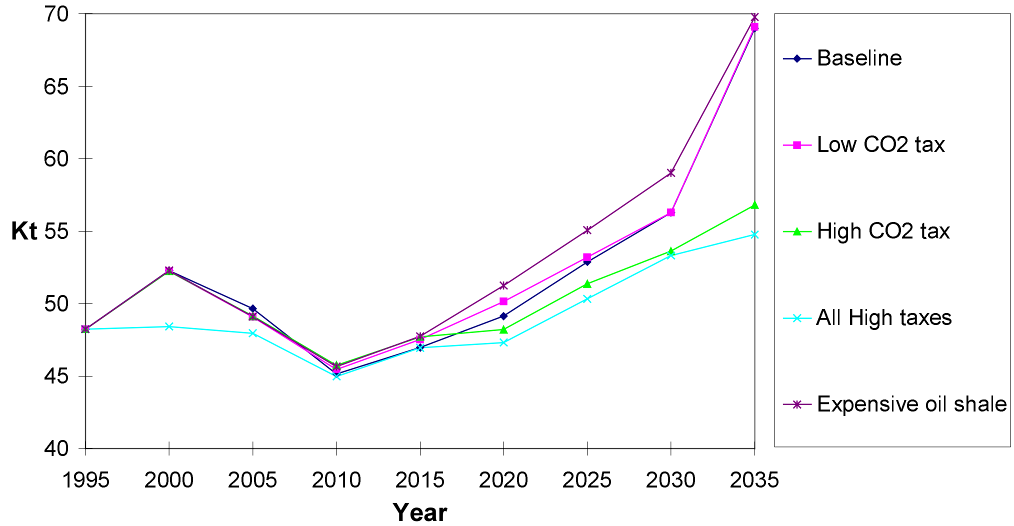


Figure 65 Total NO_X emissions from the energy system under high energy demand



8 MARKAL-MACRO results

8.1 Model input data

In addition to the data required for the representation of the Estonian energy system in MARKAL, macroeconomic data are needed to build up the MACRO model. Initial data for the MACRO model is described in Table 37 and in Table 38.

Table 37 Base year parameters

Gross Domestic product in 1995	(GDPO)	41,503 million EEK
Capital value share	(KPVS)	0.25
Initial Capital-GDP ratio	(KGDP)	2.5
Initial total Energy Costs	(ECO)	15,506 million EEK
Initial Energy Prices	(PREF)	From MARKAL run

The initial total energy costs are taken from the last MARKAL run. The initial energy prices (PREF) are used as reference prices for benchmarking MACRO model for the start year. Last MARKAL run energy prices in the first period serve as reference energy prices to the MACRO model.

Table 38 Assumed parameters

Depreciation of Capital	(DEPR)	6 %
Elasticity of Substitution	(ESUB)	0.25
Bound of demand decrease	(DMTOL)	0.5
Potential GDP-growth rates	(GROW)	see Figure 35

The Parameter DMTOL considers how much energy demand is allowed to decrease in one period. For example if it is at 0.5, which is minimum, then the energy demand can decrease to half of the value in a certain period.

The relation of energy demand and economic growth can be decoupled through changes in relative energy prices, modelled with the elasticity substitution parameter (ESUB). It determines the ease or difficulty of substitution between the capital-labour aggregate and the energy aggregate, given a change in relative prices. The difficulty in estimating the parameter (ESUB) is due to the fact that neither the energy service nor its price is statistical information. It can vary between 0 and 1. But in practice it is used between 0.25 and 0.5 (this interval is recommended by ETSAP). The higher the number, the more easily energy demand is substituted by capital and labour.

Apart from the substitution between capital-labour and energy, decoupling effects not directly caused by changes in energy prices can be distinguished. In MARKAL-MACRO the not price induced demand decoupling factors (DDF) are summarised in the parameters DDF. They are used to model technological developments and structural changes within end-use sectors that affect the level of energy demand. To generate (DDF) data the last run of the MARKAL model is needed. The Estonian MARKAL-MACRO version estimates the DDFs using the Kypreos algorithm (Kypreos, 1992). The Kypreos method includes the linkage of energy demand and GDP. DDFs are either positive, meaning that energy demand at constant prices grows slower than the GDP, or negative, meaning that it grows faster than the GDP (Vos, 1996).

8.2 Model results

The costs of emitting less CO_2 to the atmosphere represent ideally the direct costs of taking measures to reduce emissions (i.e. carbon tax) and the benefits obtained by reducing the environmental damage by reducing CO_2 emissions. The calculations with the MARKAL-MACRO model do not provide a full picture of the reduction costs. They provide only the costs directly related to the reduction and not the costs related to the external effects of CO_2 emissions since these are extremely difficult to estimate and surrounded by uncertainties.

The total CO_2 reduction costs are found by subtracting the costs of the case considered with the costs of another case, in this case the base-case. The CO_2 reduction costs in the two models are deducted in different ways. In MARKAL, the CO_2 tax revenues are included in the total energy system cost whereas in MARKAL-MACRO they are not since they are returned to the economy. According to these differences, the best measure for MARKAL is the comparison of energy system costs and for MARKAL-MACRO the comparison of the gross domestic product (Vos, 1996).

MARKAL-MACRO runs were made for baseline (model calibration), Low CO_2 tax and High CO_2 tax scenarios. Some basic results are depicted in Figure 66 to Figure 70. The main conclusions from investigating the impact of CO_2 reduction on Estonian energy system and national economy with MARKAL-MACRO are the following:

- CO_2 reduction measures will rise energy prices compared with the baseline scenario so much that energy demand must decrease.
- The higher the CO_2 tax is the more expensive reduction options will be used.
- High energy prices, costly technologies and reduced demand cause the lowering of GDP compared with baseline development.
- To follow the baseline GDP projection under mitigation scenarios the energy demand should be lower than projected initially (energy intensity of GDP must be reduced) or vice versa, to satisfy the initial demand projections under mitigation scenarios, the GDP must grow faster than projected.
- Fuel choice and technology decisions for the same mitigation scenario are somewhat different in MARKAL and MARKAL-MACRO results. MARKAL-MACRO prefers "lighter" investments.
- Compared with MARKAL results, the changes in the energy system are smoother.
- Long run CO_2 emissions differ from corresponding MARKAL results. Here the emissions under Low and High CO_2 tax scenarios are closer to each other. The differences are caused mainly by different from MARKAL use of oil shale and coal under Low CO_2 tax scenario (compare Figure 47 and Figure 68).
- In reality, Estonia's hands are not so free in reconstructing its energy system as it was assumed for model calculations. Several driving forces of energy policy like social costs of decisions, forthcoming power sector privatisation, supply security and also national security considerations, etc. could not be modelled. For example, a fast shift to imported fuels (natural gas) recommended by the model under mitigation scenarios can be unacceptable due to considerations mentioned above. Model results show us the ideal least-cost solution under certain assumptions and restrictions that can serve as a guideline for actual changes.

9 Cost of CO2 reduction

As it was mentioned already in Section 5, GHG reduction can be analysed with MARKAL in two ways:

1. Conventional approach (*The Integrated Systems Approach*), when cost data are changed. MARKAL enables to model the marginal cost of CO_2 reduction as input data in the form of CO_2 tax (see model description in Section 1.1). In that case the model finds the optimal solution for each given CO_2 marginal cost level and we can find out from the results the corresponding reduction of emissions and what changes will take place in the energy system.
2. Forced introduction of technologies (*The Partial Solution Approach*) that do not appear in the optimal solution or whose market penetration is too small under assumptions made due to their high cost. In this case cost analysis of each CO_2 reduction option can be made by comparing the total system cost and emissions data in the baseline and mitigation scenarios containing this particular option.

Figure 66 Total useful energy demand calculated by MARKAL-MACRO

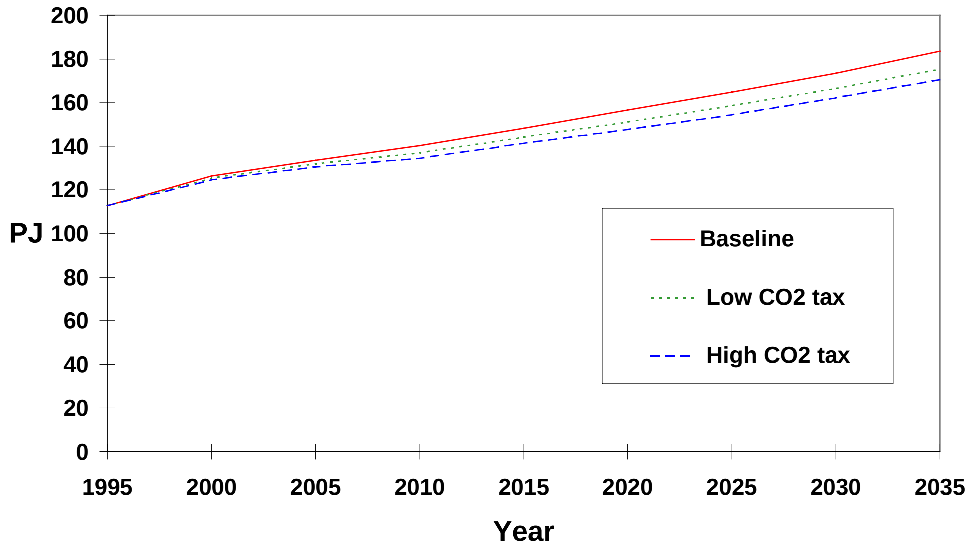


Figure 67 GDP projections calculated by MARKAL-MACRO

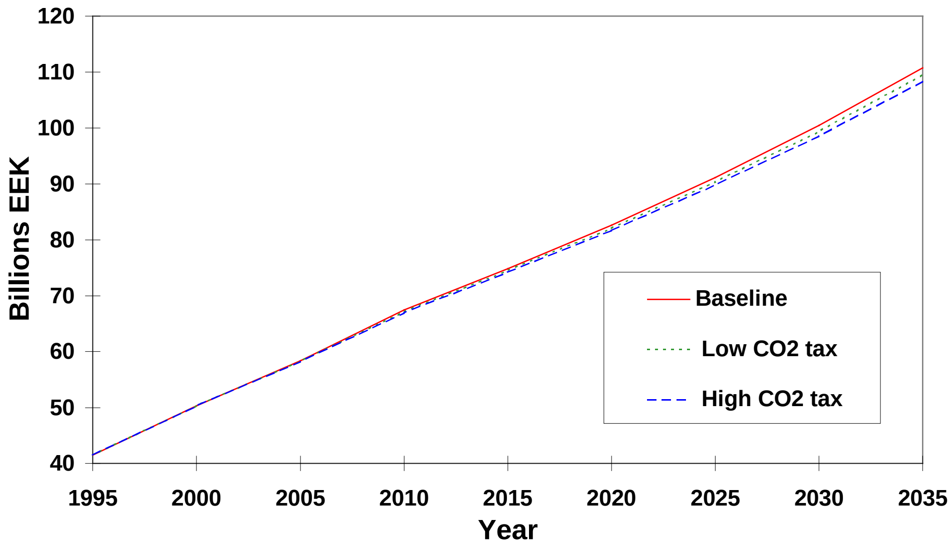


Figure 68 MARKAL-MACRO primary fuel supply under Low CO_2 Tax

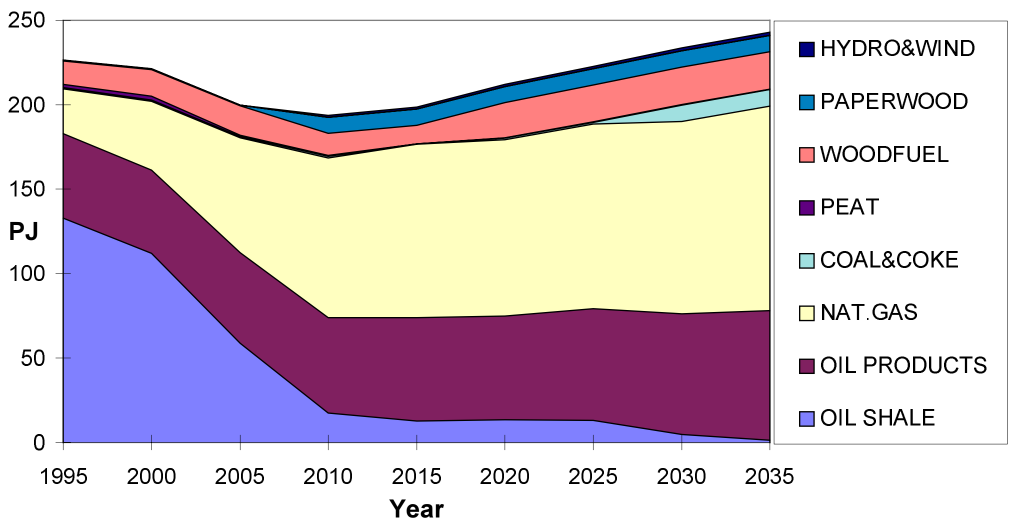


Figure 69 MARKAL-MACRO primary fuel supply under High CO_2 Tax

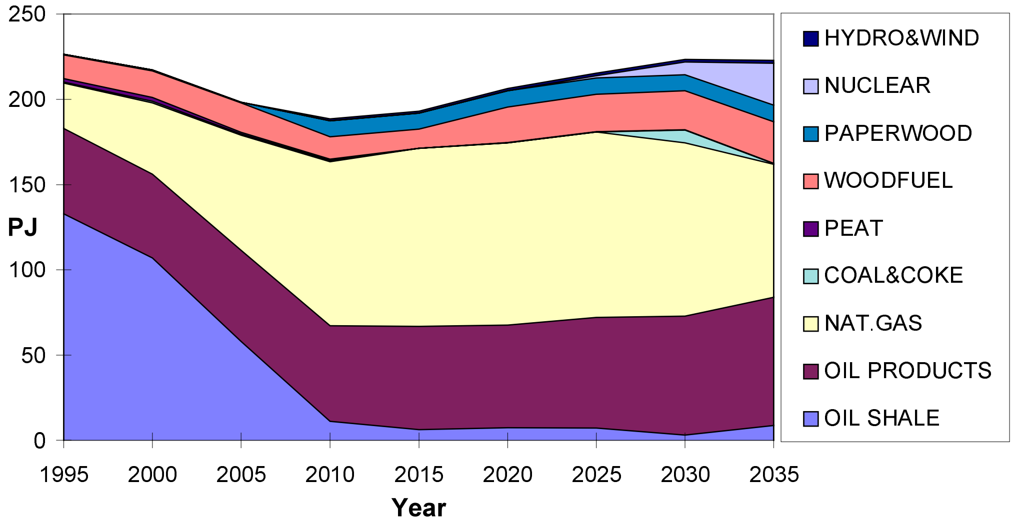
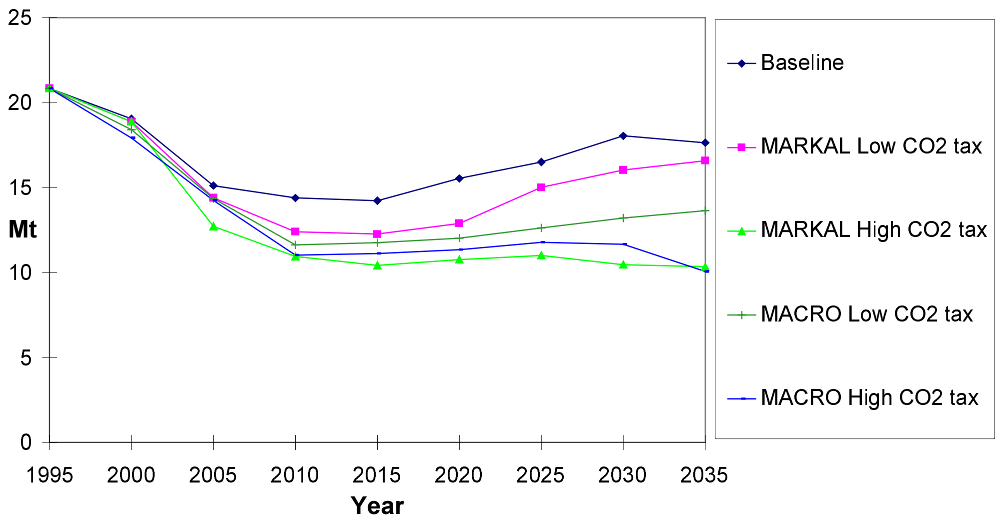


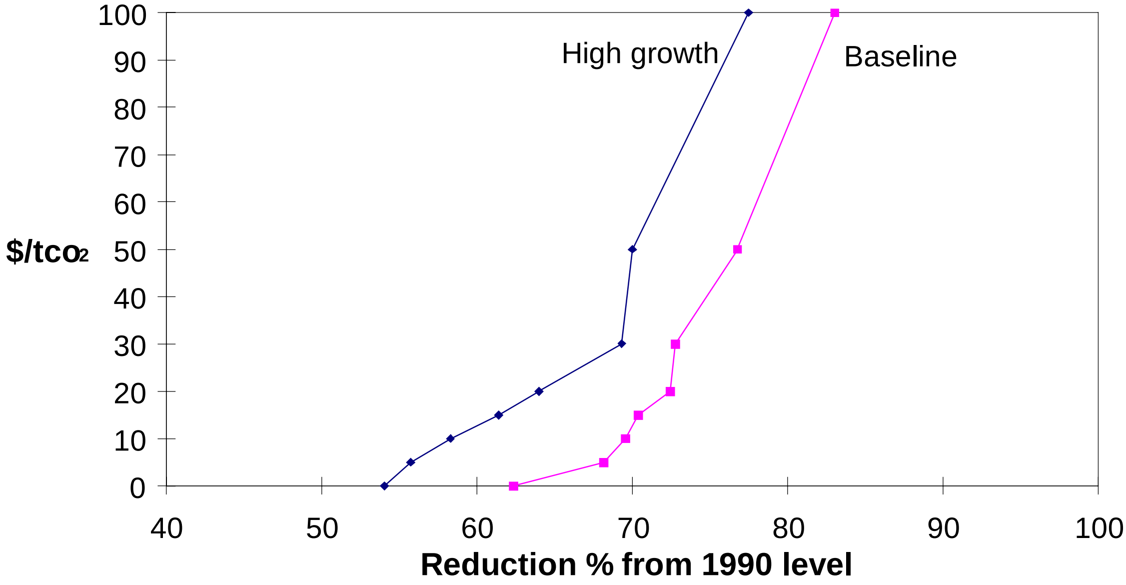
Figure 70 Total CO_2 emissions from the energy system under baseline energy demand



Here the results of both approaches are presented with bigger emphasis on the second one.

The marginal cost curves of CO_2 reduction for the year 2015 calculated using the conventional approach are depicted in Figure 71. Every cost level causes economically optimal changes in the energy system. Reduction of CO_2 is achieved due to changes in technology and fuel mix on both the supply and demand side of the system. The changes that take place in the system when CO_2 tax rises are described in Section 7: the use of natural gas will increase, wood use will grow to the sustainable limit, nuclear power will be introduced, and hydro and wind energy, high cost energy conservation measures and even biomass CHP will become attractive.

Figure 71 Marginal cost of CO_2 reduction in 2015



Marginal costs of specific CO_2 reduction options that do not appear or are not accounted in the baseline optimal solution, can be calculated in accordance with the formula from Methodological Guidelines of the present study (Technical Guidelines, 1998):

$$MRC_t = (CR'_t - CR_t) / (R_t - R'_t).$$

where

MRC_t marginal reduction cost in the year *t*,

R_t total CO_2 emissions in the year *t* under baseline scenario,

R'_t total CO_2 emissions in the year *t* under scenario with specific option,

CR_t total system cost in the year *t* under baseline scenario,

CR'_t total system cost in the year *t* under scenario with specific option.

Here R'_t and CR'_t correspond to the least cost MARKAL solution where specific reduction option is added to the baseline assumptions.

Calculations were made on a project by project basis and analysis was made for the years 2010 and 2025. Short and long term reduction options can be found in Table 39 and Table 40. The corresponding marginal CO_2 reduction cost curves are depicted in Figure 72 and Figure 73.

It should be mentioned that costs of reduction options concerning electricity export-import are fictive, because the export-import prices are confidential and also the future price projections are the authors' speculations. Saving and penetration factors, and costs of conservation measures were taken from (Strategy for Energy Conservation…, 1996). CO_2 reduction measures using natural gas as well as small hydro plants were not considered here as specific options because they were extensively introduced already under the baseline scenario.

Table 39 List of short term CO_2 reduction options comparing with the baseline scenario

ELEXP	Electricity export is restricted
PFBC	PFBC reconstruction of oil shale plants 200 MW
BIOCHP	Biomass Combined Heat and Power plant 10 MW
WIND L	Wind turbines on coastline 50 MW
ELIMP L	Electricity import 3.6 PJ at low price
ELIMP H	Electricity import 3.6 PJ at high price
CONS1	Energy conservation I (third glass to windows)
CONS2	Energy conservation II (new insulation in houses)
CONS3	Energy conservation III (temperature control valves on radiators)
CONS4	Energy conservation IV (rectification of pipe insulation in basements)
CONS5	Energy conservation V (rehabilitation of water heating systems)
CONS6	Energy conservation VI (installation of mechanical ventilation-exhaust and fresh air inlet grilles-with manual control)
CONS7	Energy conservation VII (renovation of roofs)
CONS8	Energy conservation VIII (additional attic insulation)

Table 40 List of long term CO_2 reduction options comparing with the baseline scenario

ELEXP	Electricity export is restricted
NUCLEAR	Nuclear power plant 600 MW
PFBC	PFBC reconstruction of oil shale plants 500 MW
BIOCHP	Biomass Combined Heat and Power plant 50 MW
WIND L	Wind turbines on coastline 50 MW
WIND L+S	Wind turbines on coastline 150 MW and on sea 150 MW
ELIMP L	Electricity import 7.2 PJ at low price
ELIMP H	Electricity import 7.2 PJ at high price
CONS1	Energy conservation I (third glass to windows)
CONS2	Energy conservation II (new insulation to houses)
CONS7	Energy conservation VII (renovation of roofs)
CONS8	Energy conservation VIII (additional attic insulation)

The results show that most of the energy conservation measures should be implemented. The main problem here can be the financing of those projects.

Large amounts of CO_2 emissions could be cut off by restricting electricity export and opening import instead. This option still means that CO_2 will be emitted somewhere else and it will also affect the whole economy (state budget, foreign trade balance, energy prices etc.). Changes in electricity export-import should be regulated by market.

Estonian Energy Strategy (Energy Strategy for Estonia, 1997) and Energy System Development Plan adopted in the Parliament in February 1998 (Long Term Development Plan..., 1998) both envisage the continuation of oil shale power engineering during a few decades, though not in the present volume. Considering that, replacing of CFBC reconstruction of existing power plants with PFBC reconstruction is the most attractive option in energy conversion sector for reducing CO_2, but also other emissions in the short term.

Figure 72 Marginal cost of CO_2 reduction by additional specific measures in 2010

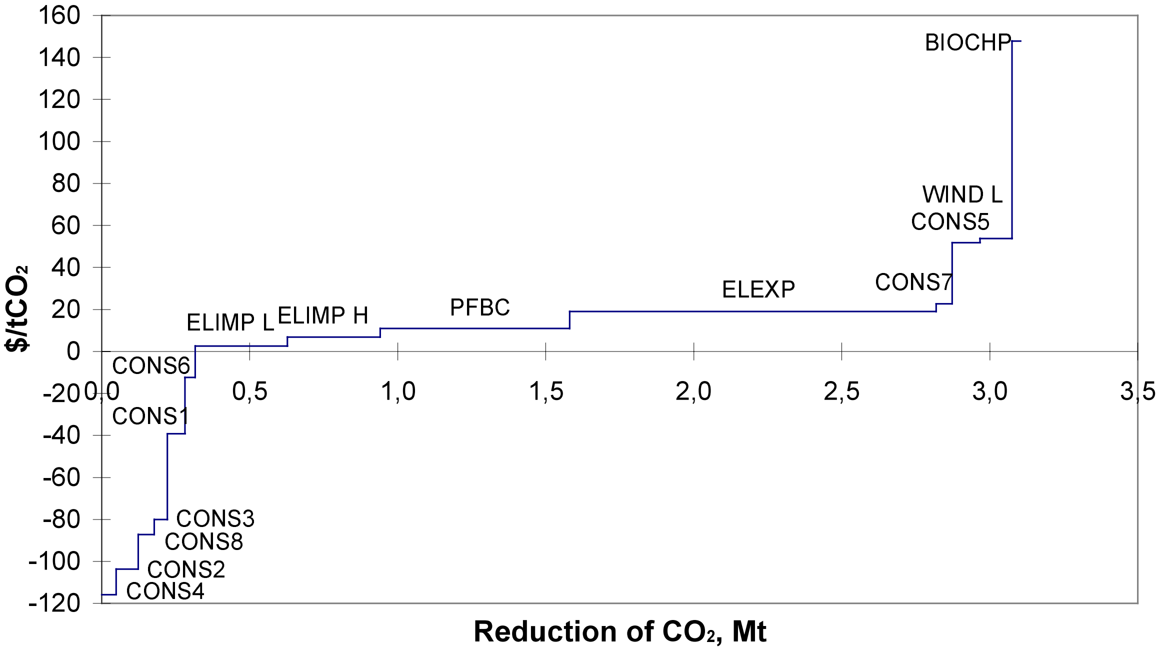
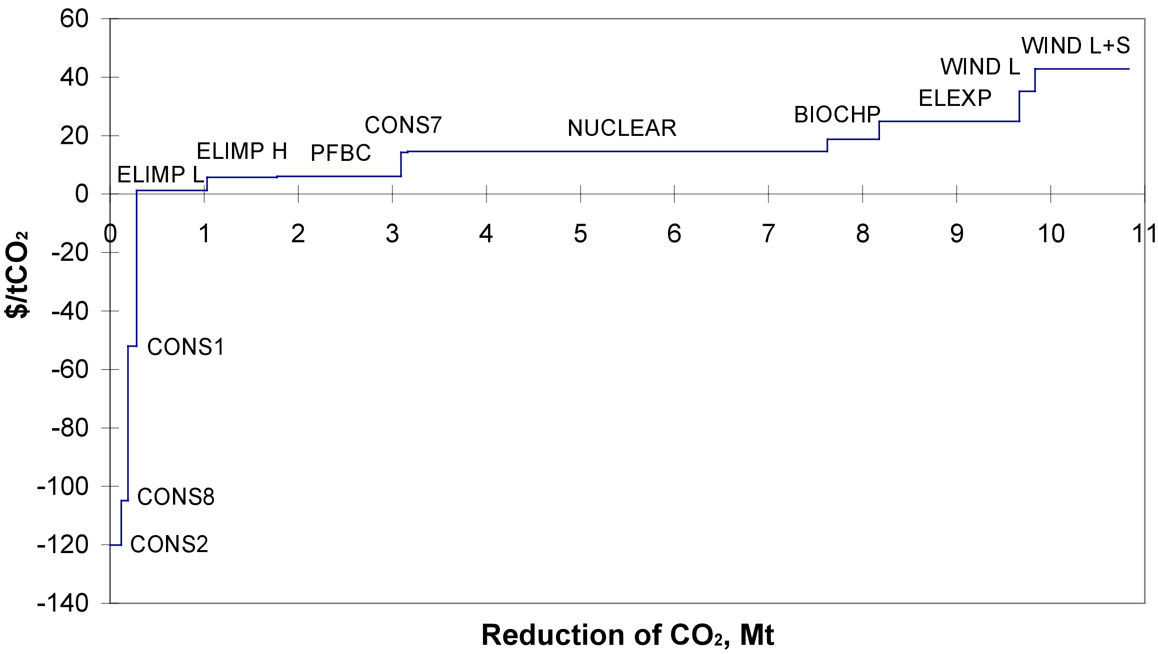


Figure 73 Marginal cost of CO_2 reduction by additional specific measures in 2025



In the long run, GHG emissions could be radically reduced by introducing nuclear power. This option needs aside economic considerations also a political decision.

Wind energy and small-scale biomass CHP along with some high cost conservation measures appear to be the most expensive measures of CO_2 reduction considered here.

Figure 72 and Figure 73 do not show the total CO_2 reduction potential correctly, because model runs for all options were made separately and compared with baseline. All options concerning power plants and electricity import and export affect strongly each other, some measures can even exclude others (e.g. PFBC replaces CFBC, but nuclear replaces almost all oil shale and coal, etc.). Total CO_2 reduction potential should be evaluated only by using the conventional approach to MARKAL modelling (see Figure 71).

Marginal costs of CO_2 reduction by the same option can be different in different years. The reason of that is mainly variation of difference between total system costs of scenarios with and without mitigation option, but also different utilisation of the option by MARKAL model. For example, the marginal cost of CO_2 reduction by expensive biomass fired CHP is much higher in 2010 than in 2025 due to low baseline system cost in 2010 and low utilisation of the plant capacity then (its energy is too expensive).

10 Conclusions from modelling

During 1990-1993, energy demand fell due to economic decline and sharp rise in the fuel and energy prices as well as a decrease in electricity exports, this resulted in ca 45% reduction of CO_2 emissions. For the same reasons, Estonia has been able to meet the requirements set in the agreements on SO_2 and NO_X emissions with no special measures or costs. To meet the more rigid SO_2 restrictions and growing energy consumption in the future, Estonia must invest in abatement and in new clean and efficient oil-shale combustion technology. Along with the old oil-shale plants closing and electricity consumption growing, other fuels will be used. The increase in energy demand then should not be fast due to constantly rising prices and efficient energy use. Measures to reduce SO_2 and NO_X emissions will also reduce CO_2. In MARKAL runs the Kyoto Agreement level of CO_2 emissions will not be exceeded. Restricted availability of imported fuels and nuclear power or enabling large scale electricity import can change the results significantly. The results presented here can also change because the database is being improved.

The real development of Estonian economy in recent years has shown quite modest GDP growth in 1995 and 1996, but a sharp increase (ca 10%) in 1997. At that time energy consumption remained stable. From today's prospective Base-case High Energy Demand scenario development of the energy system seems to be most probable for the near future. Actual changes and decisions will be strongly (still unpredictably) affected by forthcoming privatisation of the power sector. Real actions will be also affected by their social costs and political considerations not taken into account in the modelling. For example, social costs of phasing out oil shale mining, processing and power generation were uncertain and could not be considered. From the viewpoint of supply and also national security, high dependence of the power and heating sector on natural gas (economically optimal under strict environmental restrictions and taxes) is not desirable until Estonia has only one gas supplier - Russia. Changes proposed in mitigation scenarios could be implemented only when Estonia has at least one more gas supplier (e.g. another pipeline from Western Europe or construction of a Baltic Gas Ring). Increase of the share of imported fuels in the energy balance, which is especially high under mitigation scenarios, could be restricted by national foreign trade balance.

Macroeconomic Assessment of the Results

1 Development scenarios

The economic development of Estonia will depend to a large extent on different directions of the integration process of Estonia with other groups of countries like the EU, the Baltic states, Russia and the Commonwealth of Independent States (CIS). The integration of Estonia will be mainly influenced by Estonia's future role in its economic space connected with the West and the East. To cope with these uncertain developments, two scenarios, called the baseline scenario and the high energy demand growth scenario, have been developed. Both scenarios assume that global political and economic development has a strong influence on the economic development in Estonia on total and on sectoral level (Purju, 1996).

The baseline scenario assumes Estonia's close integration with Western political and economic structures, especially with the EU, while relations with Russia and other CIS countries will be relatively weak. In the framework of this scenario, the GDP is expected to grow on average 2.5% annually. The relatively modest growth of the economy is related first of all to the small size of Estonian (and the other Baltic states) market. The service sector will be of greater importance and the share of manufacturing will decrease further. Estonia will not have wider access to Russian market under the conditions of the baseline scenario and this will diminish incentives of large international companies to invest into Estonia. Scandinavian foreign investments will be dominating and influence the structure of Estonian economy.

The high energy demand growth scenario assumes that Estonia's economy will be oriented towards both the West and the East. The flows of transit goods and services and related to this services will have a greater role in the economy. Under this scenario, the average annual GDP growth is expected to be 5.3%. The closer relationships with the CIS markets will attract into Estonia more large international corporations and foreign investments of those companies will have an increasing role in the Estonian economy. On the other hand, integration with the EU and the transfer of the business culture, know-how and technology through foreign investments will provide the Estonian economy with a good basis for international trade.

The scenarios assume general trends for a very long period. However, the actual development depends on the actual political, social and economic circumstances, which may change. During the last three years Estonian development has been closer to the assumptions of the second scenario. Successful integration with the EU, substantial amount of foreign investments introducing deep structural changes in the economy and increasing transit trade have been major factors in the economic development. The growth of the GDP was 4.3% in 1995, 4.0% in 1996 and 11.4% in 1997. The growth figures seem rather high but the 30% economic decline during the first half of the 1990s due to transition from centrally planned to market economy put the basis for the growth rather low. At the same time several obstacles are still in place hindering even faster economic growth. Estonia does not have a border treaty with Russia and therefore the Estonian exports are not supported with the most favoured nation) (MFN) arrangements. Estonian exporters have to pay double tariffs for exports to Russia and for several products for which Russia has been the traditional market (food products first of all) this is economically rather painful. Elimination of those problems through negotiations or the WTO membership (such a treatment is considered to be discriminative between the two members of the WTO, but Estonia and Russia are still only looking for the membership of the WTO in 1998) could promote the economic growth in Estonia further.

2 Changes in the structure of economy and their influence on the demand of energy

During the deep structural changes in the Estonian economy in the last seven to eight years the following two basic trends have been dominating:

1. decline of output in the traditional sectors like agriculture and manufacturing;
2. a rapid growth of underdeveloped in planned economies activities like trade, finance and insurance, business services, transport and communications.

The future development will most likely base on further fast development of different services. Some restoration of the role of manufacturing could occur in the next years. The extent and speed of those tendencies will be different under the two scenarios. The conditions of the high energy demand growth scenario will favour transport and communications needed for serving transit trade. Also several branches of manufacturing can be supported by those conditions like foodstuffs, textiles, machinery and chemicals (Purju, 1997).

The main industrial energy consumers are the chemical industry, other non-metallic mineral products, food industry, mining and fuels. The faster growth of those industries in the second scenario is related to wider use of Russian inputs (a new methanol plant using imported gas is a possible new production unit in this scenario). The establishment of a new paper plant and respective increase in energy demand have been assumed in both scenarios. However, the construction of a new paper plant has been until now quite a sensitive political and economic issue. The required capital for such a plant is very big (approximately 4–5 billion kroons) and too expensive for Estonian companies. International companies interested in such production have been asking guarantees form the Estonian government regarding access to forests, price of raw materials and energy. Until now the government has been fractious in providing with guarantees several companies potentially interested in such a project. The reason has been partly that the government has been claiming it avoids industrial policy type of interventionism. Also the political will has been neutrality in respect to different industries in supporting their projects. The pulp and paper industry is one of the main exporters of Finland. The project has been sensitive also due to the closeness of Estonia to Scandinavian paper producing companies. At the same time, Estonia enjoys several advantages for such production: historical experience, forest resources, relatively cheap energy, close Russian market and timber.

As to other sectors, trade (accounting for 17% of the 1996 output) and construction (5%) have performed best in recent years. Construction will grow fast in the high growth scenario, at a rate higher than the general growth level.

In the transport sector, the complementary nature of water transport to railway and road transportation has been considered. The goods that are objects of transit trade will arrive by ships from the West and will be transported by railway further from Estonian harbours. The goods travelling from east to west will arrive mainly by railway and will be transported further by sea. More than 80% of transit trade will be carried from west to east and vice verse; while the share of goods carried from north to south and vice versa will be limited. The last directions, called Via Baltica, have been discussed as a perspective route but in reality transit trade has been using other directions. Widening of trade in the future and better transport services (especially on borders of the Baltic states and Poland) could make that direction more attractive and increase trade flows. As long as the west-east route is dominating, the share of transportation in the energy demand will depend heavily on the conditions the described in the scenarios.

Dynamics of electricity consumption reflects the general trend of economy during the transition period. The decline in the consumption of electricity has been especially steep in industry and agriculture. On the other hand, the consumption of electricity has been rather stable in construction and transportation. In the case of construction, although construction activities have decreased, the increasing use of different new electrical equipment and mechanisms (new technological level) have increased the consumption of electricity. The same was partly true in the case of households - consumption of electricity increased during the period of economic depression and decline of incomes.

The following ideas seem to be relevant for the future perspectives of the fuel industry and power engineering. First, during a shorter period - until Estonia becomes a member of the EU (probably in the period 2002-2004) - oil shale is considered to be the most efficient energy source (especially without big investments). The efficiency of other local fuels (peat and wood) seems to be overestimated and they do not offer a real alternative for at least next ten to fifteen years.

3 Prices of oil shale, other fuels and electricity

Oil shale is the most important primary source of energy, which provided 63% of the total fuel consumption in 1996. Comparison of energy prices in Estonia gives an estimate that the price of oil shale in US$/ MW·h was at the level of 25 to 60% of the price of coal, at the level of 25 to 45% of the price of heavy fuel oil and 20% of the price of natural gas. The forecasts of oil shale prices were made by Reinsalu (1996), and raised by 10% by Liik (1998). The price of oil shale is forecast to approximately double by the year 2015 and treble by 2035 as compared with 1995. The actual oil shale price increased from the average price of 68.0 kroons per tonne on 1 January 1995 to 74.8 kroons on 1 October 1995, to 86 kroons in 1996 and to 116 kroons in 1997. In 2007, the price is expected to be 150 kroons (Laur and Tenno, 1997). The price increase was already 1.7-fold in 1996 compared to 1 January 1995 (in current prices). The expected two-fold nominal price (not the inflation free real price considered in MARKAL) increase will be achieved, according to Laur and Tenno (1997), in 2007. From those figures we can conclude that the probability of the Expensive Oil Shale scenario (see Chapter 5) is very high.

The price of electricity is a very critical issue of perspective investments. In the general framework of price adjustments it is forecast by several institutions (Bank of Estonia, Estonian Institute of Future Studies) that inflation may be around 10% after the year 2000, which also means that the main part of price adjustment will be completed before that time. Of course, prices of non-tradables could be still lower in comparison with developed countries, but the future price adjustments could be realised under a lower growth of the consumer price index (CPI) and during a longer period. Also the government’s economic policy is an important factor in these developments. As Estonia has declared and introduced a privatisation program of infrastructure objects (including power engineering), one presumption of that program is a rather fast increase of the price of electricity to the competitive level for investors.

Also now Estonia, Latvia and Lithuania, but also Russia, are linked into a general network. Estonia exported electricity to Latvia (53% of the electricity exports in 1995) and Russia (47%). The price of electricity in Latvia (61 Estonian cents per kW·h in May 1996) and in Lithuania (53 Estonian cents per kW·h) has been somewhat higher than in Estonia (45 cents for kW·h). In Russia the price of electricity is lower, but Estonia had with Russia barter transaction selling electricity at a lower price and purchasing oil shale from Russia also at a lower price. Such trade has been criticised because the output of Estonian mines was lower than their production capacities. Larger trade of electricity is considered to be a rather influential issue due to the price differences and need for some kind of barter trade, which increases dependence on political issues. As Lithuania has the Ignalina nuclear power plant, which produces relatively cheap electricity with risky technology, Estonian export to Lithuania may become important if Ignalina has to diminish its output due to safety requirements.

Trends of oil shale and electricity prices have some specific features due to convergence of prices in Estonia with other market economies. The relative price of primary and secondary energy was in the former Soviet Union lower than in Western countries. Price jumps in 1991 and 1992 changed that situation drastically , but later the increase in those prices has been lower than the consumer price index (CPI) making energy relatively cheaper compared with other prices in the basket of the CPI, especially between 1992 and 1996. Later, due to lower inflation, the trends of electricity and oil shale price indexes have been close to the CPI. As the production price index (PPI) has been lower than the CPI, the tendency of the increasing energy costs also in relative terms, in addition to absolute costs, has emerged. As Estonian prices are still in average at the 60% level of the prices of developed countries, a further price convergence will follow, which will have a strong influence on comparative advantages/disadvantages of prices of Estonian fuels and electricity versus world market prices of different fuels.

As Estonia has had fixed foreign exchange rate at the same level - DEM 1 = EEK 8 -- since June 1992 until spring 1998, the nominal price increase turned to be in international terms (and particularly with the DEM terms) at the same level with real increases. So, for example the average wages increased from 802 kroons in the fourth quarter of 1992 to 4027 kroons in the fourth quarter of 1997 (five-fold increase). The share of wage cost has been in mining 30% of the total costs (Eesti tööstus, 1997). The increase in the mining industry has been at the same level, the costs of oil shale mining increased only due to wage increase 1.5 times. The fixed exchange rate arrangement means in a country where inflation is several times higher than in its trade partners (Estonia compared to Germany) that the effect of nominal price increases on the cost and price level is very close to real price increases. Or in other words, the difference between Estonian inflation and the inflation in developed countries should be considered as a real price increase in the model.

4 The fixed exchange rate and the balance of payments problem

The fixed exchange rate of DEM 1 = EEK 8, which was introduced in June 1992, is valid also in 1998. At the same time Estonia has had a considerable level of inflation also after the monetary reform. Inflation was 89.8% (here it should be remembered that for the whole 1992 inflation was 952%) since June 1992 until December 1992, 35.7% in 1993, 41.7% in 1994, 28.9% in 1995, 14.8% in 1996 and 12.5% in 1997. As those figures have been higher than those of Estonian main trade partners (more than 50% of Estonian foreign trade has been with the EU), the appreciation of the real effective foreign exchange rate has been the result.

The Bank of Estonia estimated the dynamics of real effective exchange rate calculated on the basis of changes in the exchange rates of the Estonian kroon and the respective currencies of Estonia's main trade partners and the CPI of Estonia and the respective countries (Overview of Estonian economy, 1997). In December 1997, the index of the average real exchange rate was close to 4.0 compared with the pre-reform level of June 1992. At the same time, the value of the index with Western partners (including Finland, Sweden, Germany, Denmark and The Netherlands) was close to 6.0 and with the transition economy partners (including Russia, Latvia and Lithuania) it was 0.8. This means that while in relation to Western partners the real value of the kroon was appreciated, the Estonian goods and services became relatively cheaper in Eastern markets due to the fact that the higher than in Estonia inflation was accompanied with less deep depreciation of the currencies of some countries (Lithuania) or, as in the case of Latvia, the appreciation of the lat in relation to the DEM (and the Estonian kroon) was relatively bigger than the difference of inflation in Estonia and Latvia (in Latvia inflation was lower). With Russia the value of the index means that the Estonian goods became relatively cheaper in Russia during three years.

The real exchange rate appreciation hampers exports, increases imports, worsens the foreign trade deficit and may lead to a balance of payments crisis. In Estonian case, the 13% current account deficit to the GDP was the result in 1997. The foreign trade deficit was at the level of 33.2% of the GDP. The surplus of services diminished the current account deficit and the capital and financial account surplus, larger than the current account deficit, kept the balance of payments positive. As a result, the foreign currency reserves and the money supply, linked to the changes in currency reserves under currency board arrangement, increased. However, the very deep current account deficit, much larger than in Mexico in 1994 or in the Czech Republic during the 1997 currency crisis, is a risky phenomenon for future development. One Estonian advantages in such a situation is that approximately two thirds of domestically consumed energy is based on Estonian primary energy sources (first of all, oil shale).

5 The foreign trade balance

Estonian foreign has been growing very rapidly. After the monetary reform in 1992, exports grew 96% and imports 135% in 1993, 59% and 81% respectively in 1994, 25% and 35% in 1995, 18.8% and 32.5% in 1996 and 32.3% and 32.7% in 1997 in comparison with the previous year (Foreign Trade..., 1996). As Estonia has had since 1992 the same fixed exchange rate, this increase in foreign trade occurred also in convertible currency terms (US$ or DEM). The growth of exports during the time the currency appreciated seems to be at first glance paradoxical. However, here the initial conditions of the economy and the general framework of development should be taken into account. Estonia started its reorientation toward Western markets in a situation where a very large share of its production was unacceptable to the markets of developed countries; Estonian enterprises had to change substantially the character of their products. Very many enterprises changed from being manufacturers of final and semi-final products to being subcontractors of Western firms. Several raw materials (unprocessed wood, scrap metals) formed a very large share of Estonian exports.

The strongly undervalued foreign exchange rate (in comparison to the estimated PPP), which made Estonian inputs very cheap, was also of great importance giving the increase in the average wage (US$ 40/DEM 60–70 in June 1992, to US$ 280/ DEM 500 at the end of 1997) a rather influential cost-side effect in labour-intensive industries. In other industries, this effect was certainly shadowed by the positive effects of institutional changes (trade agreements, know-how inflow) and changes of output due to new investments, technologies and materials.

The structure of Estonian imports has been determined by the necessity to purchase fuel and other raw materials (e.g. cotton as an important input for Estonia's rather large textile industry). Machinery, mechanical appliances and electrical equipment have also been important imports. Right after the monetary reform, the purchasing power of Estonian economic agents was artificially set very low. Domestic inflation and also increase in real incomes since 1995 also increased demand for imported goods. Evidence for this was the increasing value of imported consumer goods, which was also a reason for the growth in the foreign trade deficit.

The geographical pattern of Estonian foreign trade changed very substantially in 1992. Reorientation to the Western market was not easy and most producers were not ready for it. Finland played a very important role, encouraged by its knowledge of these markets and its linguistic similarity. Finland's market share in 1991 was 2.3% of Estonian exports and 2.0% of its imports increasing to 21.2% and 22.6% respectively in 1992. During the next few years Finland's share remained rather close to these figures: Finland accounted in 1997 for 21.4% of the Estonian exports and 32.6% of the imports. Finland also acted as mediator for Estonian entrepreneurs. Several products imported from Finland are only packed or processed in Finland (vegetables, for example) but are registered as Finnish imports. On the other hand, some Estonian exports are transferred from Finland to other countries. Another reason why Finland's share is high in the Estonian foreign trade is the large number of foreign direct investments from Finland in Estonia. Nevertheless, in amount of foreign direct investment in Estonia, Sweden is the leading country, with Finland only second.

Very often Estonian producers and traders who started seeking foreign contacts in Finland later moved on to Scandinavian and other West European countries. Among Estonian exports to Finland, machinery and mechanical appliances (30.6%), textiles and textile products (25.7%) were the leading items in 1997. Both are related to subcontracts by which a large number of Estonian producers manufacture semi-final products for Finnish enterprises and export them to Finland. The share of base metals (mainly scrap metal), important in 1992 and 1993, made up only 9.0% in 1997. Wood and articles of wood accounted for 15.5% of Estonian export to Finland in 1997. The structure of Estonian exports to Sweden, Estonia's third largest foreign-trade partner, is rather similar. The leading export items are wood and articles of wood (27.9% in 1997) and textiles and articles thereof (26.2%). Export has been relatively more important than in the case of Finland.

Russia's share of Estonian foreign trade declined dramatically in 1992, but since then it has been rather stable. Russia furnished 17.5% of Estonian imports and received 26.1% of Estonian exports in 1995. For certain items, Estonian producers and traders are interested in having economic linkages with Russia. Among 1995 Estonian exports to Russia, food products formed 33.6% and transport vehicles 18.4% (mainly as re-export). Among 1995 Estonian imports the dominant item was mineral products (mainly oil), making up 54.8% Estonian imports from Russia.

Trade with the other Baltic countries, Latvia and Lithuania, has been rather modest. In 1995, Latvia's share of Estonian exports was 7.6% and in imports 2.0%. To Latvia Estonia exports electricity, which was the largest single article in 1992 and 1993. In 1995 the share of electricity fell, and the leading items became food products and chemicals. Estonia's share of food products increased particularly in 1994 and 1995 because Estonia had problems with exporting its food products to Russia, its traditional market area for foodstuffs, and the higher Latvian price level attracted Estonian food producers and traders.

Lithuania's share was 4.7% of exports and 1.6% of imports. Earlier, Estonia received a rather important part of its gasoline from the Mazeikai refinery in Lithuania. Now the share of gasoline imported from Lithuania has decreased. Mineral products made up 38.7% of Estonian imports from Lithuania in 1994, but only 10.0% in 1995. Textiles and textile products (23.4%) were the leading item in 1995. Estonia exports to Lithuania chemicals (25.0% in 1995) and food products.

Germany has been a target for textiles, wood and metal exports (these items comprised 19.3, 16.8 and 14.7% of Estonia's 1995 exports to Germany). Estonia imported from Germany mainly machinery and mechanical appliances (24.0% of its imports from Germany), food products (15.6%) and textiles and textile products (15.1%). Historically, between the two World Wars, Germany was the main trading partner of the Republic of Estonia.

By geographical regions, until 1994 EFTA countries dominated in Estonian foreign trade with 30.9% of its exports and 40.6% of its imports in 1994. In 1994, the EU countries received 19.0% of Estonia's exports and furnished 23.8% of its imports. As Estonia's main trading partners, Finland and Sweden, but also Austria, joined the EU from 1 January 1995, the share of members of this union was in 1995 as high as 53.8% of Estonian exports and 66.0% of its imports. In 1996 and 1997, the share of the EU was lower and the share of the CIS higher. Partly the reason was the different competitiveness of Estonian goods due to the different pattern of the real exchange rates.

6 The relationship between the foreign trade balance and energy

For our study, the main interest is the influence of different solutions to the foreign trade balance. The starting point for calculations is the year 1995. Then the share of the domestically produced primary energy was 71%, including oil shale with 63% and wood and peat with 8%. The share of imported primary energy was 29% (Energy sector, 1998). Fuels created 3.7 billion kroons or 9.5% of Estonian imports in 1996. We assume that imports will increase at the same level with economic growth in the respective scenarios. As the price increases of imports and fuel have been considered to be equal, we used for calculations only real growth figures. The results according to the baseline scenarios and several other assumptions would have the following influence on foreign trade.

6.1 Base demand scenario

6.1.1 Base case demand scenario

The general demand will be in 2005 10% lower in PJ-s than in 1995 due to modest economic growth and more effective use of energy. The share of domestic fuels will decrease to 50% of the supply. The share of imported fuels will account for 12% of the total imports.

The general demand will be in 2020 at the same level as in 1995. The share of domestic fuels will be at the level of 50%. The imported fuels will make up 9.2% of the total imports.

6.1.2 Base case demand scenario with low CO_2 tax

The general demand will be in 2005 10% lower in PJ-s than in 1995 due to modest economic growth and more effective use of energy. The share of domestic fuels will decrease to 33% of the demand. The imported fuels will make up 16% of the total imports.

The general demand will be in 2020 at the same level as in 1995. The share of domestic fuels will be at the level of 25%. Share of imported fuels will make up 13.8% of the total imports.

6.1.3 Base case demand scenario with high CO_2 tax

The general demand will be in 2005 10% lower in PJ-s than in 1995 due to modest economic growth and more effective use of energy. The share of domestic fuels will fall to 20% of the demand. The share of imported fuels will be 19% of the total imports.

The general demand will not change in 2020. The share of domestic fuels will be at the level of 10%. The share of imported fuels will be 15.8% of the total imports.

6.1.4 Base case demand scenario with all high taxes

The general demand will be in 2005 10% lower in PJ-s than in 1995 due to modest economic growth and more effective use of energy. The share of domestic fuels will fall to 20% of the demand. The imported fuels will account for 19% of the total imports.

The general demand will not change in 2020. The share of domestic fuels will be at the level of 10%. The imported fuels will make up 15.8% of the total imports.

6.2 High energy demand growth scenario

6.2.1 High energy demand growth scenario

The general demand will be in 2005 at the same level as in 1995 due to fast economic growth and more effective use of energy. The share of domestic fuels will decrease to 33% of the demand. The imported fuels will make up 13.9% of the total imports.

The general demand will be in 2020 30% higher than in 1995. The share of domestic fuels will be at the level of 33%. The imported fuels will account for 8.3% of the total imports.

6.2.2 High energy demand growth with low CO_2 tax

The general demand will be in 2005 at the same level as in 1995 due to more effective use of energy. The share of domestic fuels will fall to 25% of the demand. The share of imported fuels will be 10.3% of the total imports.

The general demand will be in 2020 30% higher than in 1995. The share of domestic fuels will be at the level of 25%. The share of imported fuels will account for 9.3% of the total imports.

6.2.3 High energy demand with high CO_2 tax

The general demand will be in 2005 at the same level in PJ-s than in 1995 due to modest economic growth and more effective use of energy. The share of domestic fuels will decrease to 20% of the demand. The share of imported fuels will make up 16.2% of the total imports.

The general demand will be in 2020 10% higher than in 1995. The share of domestic fuels will be at the level of 10%. The imported fuels will account for 9.4% of the total imports.

6.2.4 High energy demand with all high taxes

The general demand will be in 2005 at the level of 1995 in PJ-s due to modest economic growth and more effective use of energy. The share of domestic fuels will decrease to 20% of the demand. The share of imported fuels will be 16.2% of the total imports.

The general demand will be in 2020 5% higher than in 1995. The share of domestic fuels will be at the level of 10%. The share of imported fuels will be 8.9% of the total imports.

7 Share of energy production in the GDP

The electricity, gas, water supply, mining and quarrying created 5.1% of the GDP in 1996. The importance of energy production and services related to energy consumption is somehow higher than their explicit share in the GDP. The restructuring of the energy system would add through construction and different services some additional value to the GDP.

The share of energy production in the GDP has decreased partly as a result of a general economic decline of the Estonian economy and partly as a result of structural changes in the energy demand. For example, oil shale mining decreased two times if we compare the level of the 1980s with 1996. The decline in the amount energy produced from oil shale was at the same level. On the other hand, in the structure of economy the share of trade, financial services and other sectors with relatively low intensity of energy increased and the share of more energy intensive sectors like manufacturing and agriculture fell. Those structural changes diminished energy demand and the share of energy production in the GDP.

Very substantial changes occurred in Estonian relative prices. As energy prices have been regulated by the state or municipalities, the general increase of those prices has been more modest than the increase in prices determined by markets. The price of energy started to be relatively lower in comparison with other prices. That makes the share of energy production also smaller in the GDP. Considering this difference in relative prices we could say that the share of energy production could be approximately one third higher than it is on the basis of current prices.

8 Energy intensity of industries

Estonian economy was rather energy intensive in the Soviet period. One reason for that was the relatively low prices of different fuels and electricity compared with prices of other goods and services. In 1996, the share of purchased fuels and energy created 7.5% of the total production costs in manufacturing. In mining, the share of respective costs was 12.8% and in power engineering, where those costs are main inputs, their share was 57.6%. In manufacturing, the pulp and paper industry has the highest share of energy cost in total costs – 19.2% in 1996. Other more intensive users of energy have been non-metal material processing industry with 15.4%, the chemical industry with 14.4% and the textile industry with 11.7% of total costs. Those industries, except the textile industry, will increase their share in Estonian output by forecasts. Though, the economy of respective costs, especially in energy intensive industries, could be a main factor for diminishing energy demand and through that also mitigate the emission of the GHG. Increase in energy prices and technological changes in economy are interrelated determinants for such developments.

9 Investments and savings

The amount of domestic savings is about 16% of the GDP, which was substantially below the high investment rates of about 29% in 1997. The difference is covered by net foreign direct investment inflows. The foreign loans are at the level of 5% of the GDP (Eesti Pank Bulletin, 1997). On the one hand, this shows that the investments and economic growth have been based substantially on foreign savings. On other hand, the country's lending position is still very good, which makes it possible to finance large investments for foreign credits in the future.

Required investments for reconstruction only for power plants until 2015 are by estimation 13 billion kroons in the case of the baseline scenario and 16–18 billion kroons in the case of high demand growth scenario. Ignoring in calculations the price aspect and assuming equal distribution of investments during the whole period, we could evaluate the annual investments at the level of 0.8 billion kroons and 1.0–1.1 billion kroons in respective scenarios. The total capital accumulation would be 18–19 billion kroons in Estonia in 1997. On the basis of those figures we could evaluate the needed investments at the level of 4-5% of the total capital accumulation in the baseline scenario and at the level 5–6% of the total capital accumulation in the high demand growth scenario during the first years of the period of forecast. In the second scenario the faster growth of the GDP and capital accumulation will diminish the share of investments needed for reconstruction of the power plants to the level of 4–5% during the second half of the period.

Several proposals have been made to privatise the power plants to foreign investors. The importance of such an investment for the balance of payments could be evaluated on the basis of comparisons with the size of foreign direct investments (FDI). The amount of the FDI was 3.6 billion kroons in 1997. If the total amount of the necessary investments will come from abroad, its share will be 22% of the FDI in the first scenario and 27–30% in the second scenario. If we assume that the other FDI will be at the same level, the FDI into power plants will increase the total amount of the FDI by 15–20%. In case the Estonian state keeps 51% of the share capital, the influence of the FDI related to the reconstruction of the power plants will be two times smaller.

Anyway, it is possible to make a conclusion that the required investments for the reconstruction of the power plants are substantial if we compare respective figures with other indicators of the Estonian economy. Therefore finding Estonian private investors who could guarantee respective necessary investments is a rather critical issue. The FDI will have quite a strong effect on Estonian balance of payments (keeping in mind the 8.5 billion kroons or 13% of the GDP current account deficit in 1997).

10 Economic influence of different taxation schemes

According to international agreements Estonia must reduce its SO_2 emission by 50% to 1997 and by 80% to 2005 from the 1980 level. The NO_X emissions are not allowed to exceed the 1987 level. According to the Kyoto agreement Estonia's CO_2 emission in 2010 must be at least 8% lower than in 1990.

The figures in Tables 41 to 43 describe the influence of different taxes on the total amount of emissions and tax levels (see also Chapter 5 on MARKAL model). Under this project the following mitigation scenarios have been considered:

Low CO_2 tax case with 4 US$ per tonne starting from 2005 (56 EEK at current exchange rate with US$).

High CO_2 tax case with 4 US$ per tonne starting from 2005 and 20 US$ per tonne starting from 2015 (linear interpolation between 2005 and 2015).

All high taxes with 5700 US per tonne in 2010 for NOx (79800 EEK) and with 4000 US$ per tonne (56000 EEK) for SO_2 in 2010 plus high CO_2 tax case.

In the first two cases, the 1995 level of SO_2 (31.9 EEK/tonne) and NO_X (73.2 EEK/tonne) taxes with 20% annual growth were used to calculate the respective taxes in 2005, 2010 and 2015.

Table 41 Taxes in different taxation scenarios in the year 2005

Scenario	Low CO_2 tax		High CO_2 tax		All high Taxes	
	Emission kt	Tax MEEK	Emission kt	Tax MEEK	Emission kt	Tax MEEK
CO_2	14405	807	12724	713	12270	687
SO_2	47	6	31	4	25	3
NO_X	44	14	43	13	42	13

Table 42 Taxes in different taxation scenarios in the year 2010

Scenario	Low CO2 tax		High CO2 tax		All high Taxes	
	Emission kt	Tax MEEK	Emission kt	Tax MEEK	Emission kt	Tax MEEK
CO2	12412	695	10956	1840	11335	1904
SO2	14	5	14	5	11	628
NOX	38	29	38	29	37	2,963

Table 43 Taxes in different taxation scenarios in the year 2015

Scenario	Low CO_2 tax		High CO_2 tax		All high Taxes	
	Emission kt	Tax MEEK	Emission kt	Tax MEEK	Emission kt	Tax MEEK
CO_2	12268	687	10425	2919	11361	3181
SO_2	14	12	14	12	11	611
NO_X	37	72	38	73	36	2898

Figures in Tables 41 to 43 evaluate costs related to taxes for emission of different components per year. Also the MARKAL model takes those estimates into account and huge costs related to emission taxes starting from 2010 in high tax scenarios are a main reason for low competitiveness of oil shale based power engineering.

No C, CO_2 or energy tax has been introduced in Estonia up till now. As there is a rather high probability that the EU will introduce respective taxes, one possible scheme to prepare better for such a change of economic policy could be introduction of respective taxes in Estonia at low level even earlier. The main problem of the present situation is that it would create wrong expectations of investors about the potential profitability of the energy system. As we mentioned before, the close to monopoly structure of the energy market could pass the burden of price increase due to taxation to consumers. On the other hand, several forecasts foresee a rather high increase in energy prices anyway. That could create strong social tensions, because there is also structural problem of prices for energy, especially electricity between industrial consumers and households. As the price scheme of energy supported the consumers in past even now the prices for households and industries are close to each other. Taking into account the distribution cost and other costs for households, the market price for those consumers should be remarkably higher than for industries. That means an even higher price increase for household due to adjustment of price structure to real costs.

11 The market structure and tax burden

The wholesale value of electricity produced in Estonia was approximately 4 billion kroons in 1996. Accepting price and output growth scenarios presented in the framework of this research, the value of electricity would be around 10 billion kroons in 2010 without emission taxes. The predominant source of carbon dioxide in Estonia is the energy system (more than 90% in 1996). On the other hand, oil shale based production of electricity is the main source of emission inside the energy system. The total sum of taxes paid in 2010 will make up 7% of the value of electricity in low CO_2 tax scenario, 19% in high CO_2 tax scenario and 55% in the all high taxes scenario. Considering minimal changes in electricity price and output between 2010 and 2015, the total amount of paid taxes could reach 65 % (all high taxes) of the value of production in 2015.

The MARKAL model offers under those circumstances the change of primary energy sources. In our analysis we could consider those figures as an estimate of opportunity cost of the methods applied for restructuring energy system and economising consumption of energy. However, we could analyse those problems also in the framework of energy market structure. There is under consideration a business plan of privatisation of two largest power plants to a foreign company with the guarantee of 75% of the market until 2006 and 50% until 2013. If that plan is accepted, the access to the energy market of new producers using different from oil shale primary energy sources would be rather complicated and the dynamics of prices will depend on the strategy of the monopoly. The consumers have to take the major part of the additional tax burden due to emission taxes.

Another question is what mitigation scenarios will be applied in the framework of different tax scenarios. The general forecast is that those scenarios will put very strong emphasis on energy demand and especially on measures related to improved energy use management. Although investments into energy intensive industries have been forecast in both scenarios of economic development, the high tax on emission could postpone or even stop the respective projects (methanol plant or pulp and paper mill included into energy demand side).

Estonian integration with the EU requires attention to the principles in the fields of energy policy like competitiveness at the energy market, energy use in conformity with the country's economic situation and consumer solvency, reliable supply and security reserve, environment protection and safety.

In 1997 the Estonian Energy Act was passed. It includes the principles of the EU energy policy like free access to energy market, the obligation of the market leader to make its product prices publicly known, the obligation to distinguish production, transfer and distribution costs, price formation (including energy production, environmental protection and safety regulations costs). The enforcement of respective regulations could balance the interest of producers and consumers on the energy market.

12 Employment

The oil shale complex and power engineering based on oil shale hire altogether close to 10000 employees (7000 of them in oil shale mines and 3000 in power plants). That figure makes up approximately 1.6% of Estonian total employment being thus not very significant. If Estonia closed down those fields, unemployment would increase from 10% to 11.6%. On the other hand, oil shale mines and plants stations are located in the very critical north-eastern part of Estonia where the potential of social and political tensions is high and unemployment exceeds the average figure of the country. In that region those employees create approximately 15% of the labour force and by estimation approximately half of them would not find a new job in the case of closing down respective industries. Unemployment in Ida-Viru County would increase from 15% to 22–23%.

On the other hand, there could be even higher indirect effects on employment. The higher price of energy from other than oil shale primary energy sources would create an additional increase in energy prices and thus diminish the competitiveness of Estonian economy, especially manufacturing. The result will be diminishing output and smaller employment. The number of additional unemployed persons could be at least equal with those fired as a result of closing down oil shale mines and electricity plants in Northeast Estonia.

The employment in Northeast Estonia should be considered as one of the politically most sensitive areas in Estonia. As business activity there is at a relatively low level, potential replacement of lost working places due to discontinued oil shale based energy production by new activities in the service sector or other areas is low. This means that the result would be an area with a very high level of permanent unemployment.

13 Alternative energy sources

13.1.1 Renewable resources

Estonian main renewable energy sources suitable for commercial energy production are peat, wood, wind and water. The biggest resource is that of wind. There are enough sites where wind energy could be harnessed to produce more than 1 TW·h electricity without conflicting with other requirements. However, limits are set by technical and financial factors, and therefore only some 3% of the present Estonian electricity production could be achieved using wind turbines.

Wood resources are also promising as about 48% of Estonia's area is covered with forest and shrubbery and the estimated annual wood consumption for fuel could reach 22–35 PJ. Peat resources can be treated as renewable only with certain reservations because of their very slow recovering speed; however, considering that 22% of the country's area is covered with wetlands, part of the estimated 2646 PJ peat resources for combustion may be taken into use. The amount of hydro energy is very limited due to the generally flat surface of the country. As maximum 30 MW hydro power can be installed and only a few former power plants with a total capacity of 4–5 MW can be restored in the near future.

So far only a small part of the available renewable energy sources are in use. Wood and peat are predominantly used for the production of thermal energy, though peat is beginning to be burned also for electricity generation. In 1996 wood and peat accounted already for 8% of primary energy production. At present five small hydro power plants with a total capacity of 760 kW are in operation, and the first wind turbine for commercial energy production with a capacity of 150 kW has been operating since September 1997.

The main obstacles to the development of all types of small renewable energy power plants are basically related to economic circumstances. Energy produced from renewable sources is more expensive than energy produced from traditional sources. The lack of a supporting taxation policy, scarcity of experience and know-how are additional factors preventing a wider use of those energy sources. There is no domestic industry producing hydro or wind turbines, most of the equipment has to be imported.

The increasing use of waste wood in the energy sector has promoted domestic production of equipment for biomass boilers. After a successful start also domestic production of wind turbines may be considered.

Considering the relatively extensive peat and wood stocks, low environmental hazard of their use and possible positive influence on regional development, the rising share of those fuels in primary energy balance could be considered. Especially if the all high emission taxes scenario was followed, the renewable resources could be also economically efficient in comparison with oil shale in Estonia in long run. On the other hand, low tax scenario postpones the transfer to alternative energy sources like wind and wood chips.

According to the Estonian Energy Strategy, an official document adopted by the Riigikogu, the amount of primary energy produced from renewable inputs will increase by 60% in 2010. The share of renewable resources will increase from 8% in 1996 to 13% in 2010. More uniform regional development, which is one of the political imperatives of Estonian future economic policy, will support the use of renewable resources.

We could evaluate the efficiency of renewable resources on the basis of the potential cost of emission tax paid in 2010. Assuming that the total amount of the energy produced will be the same, the economy due to avoided emission tax for 5% of energy production due to substitution of that amount with energy from renewable sources will provide us with 95 million kroon economy of less paid taxes in high CO_2 tax scenario and with 37 million kroons in low tax CO_2 scenario. Those figures are the opportunity cost of investments required to create new equipment to produce such amount of energy (wind generators etc.).

Estonia has very limited potential for hydroelectric power generation. However, harnessing of wind energy could be considered as one supplementary source of energy. Especially the western coast of Estonia and islands could be considered as potential locations for wind parks. The pricing policy should be changed to support the introduction of additional capacities using wind. As of 1996, the necessary costs for wind energy were at least two times higher than for the energy produced from oil shale. The emission taxes will introduce important changes in the relative prices of energy produced from different sources.

13.1.2 Gas

Increasing the proportion of natural gas has been motivated primarily by its environment friendliness. The larger gas consumers are producers of district and local heating consuming 60% of the imported gas, and chemical industry accounting for about 26% of gas consumption. Also MARKAL model prefers gas in almost all solutions. Those results are in accordance with presumptions of the model. Even the dominating role of natural gas in Estonian balance of primary energy would be politically acceptable, if Estonia could join the international network. At the moment Estonia is dependent on the supply of gas from Russia. The political risk could be evaluated at lower level due to the fact that *Eesti Gaas* is an international company with other owners like *Ruhrgas* and *Neste*. On the other hand, under the existing circumstances Estonian gas supply will depend on potential changes in Russian tax policy. The politically acceptable use of gas as a major energy source could occur only if Estonia has access to the gas network of the Nordic countries.

13.1.3 Nuclear power

The MARKAL model offers nuclear power as one option for mitigation of emission of CO_2. That will be achieved through reducing the production of oil shale based electricity. However, politically nuclear power is not acceptable for the majority of population. Partly that opposition is related to similar attitudes in Scandinavian countries. Another reason for negative attitude is related to the Chernobyl accident.

14 Energy conversion methods and mitigation of GHG

So far only a small part of the available renewable energy sources are in use. Wood and peat are predominantly used for the production of thermal energy, though peat is beginning to be burned also for electricity generation. In the longer perspective the government plans to increase the share of peat, wood and wind energy from the present 8% to 13% by the year 2010. Renewable energy resources are considered to give no CO_2 emissions since they have no impact on the global carbon cycle. So the substitution of some part of primary energy produced from oil shale with energy from renewable resources will be one of the main methods of the GHG mitigation.

If the share of wind and hydro power is increased in the general energy budget then every 1 kW·h will mean reduced demand for electricity produced by the oil shale fired power plants and lower GHG emission. However, no straightforward calculations about energy demand reduction can be made as besides energy production also several other factors (like transmission distance/losses, temporal production variability, management flexibility, etc.) should be taken into account. For rough estimation we can state that each 1 kW·h electricity produced by wind or hydro power instead of burning oil shale will help avoid the emission of 1350 g CO_2, 10 g fly ash, 1 g NO_x and 9 g SO_2 at oil shale power plants applying the present combustion technology.

Wood and peat are usually burned at boiler houses where the most common fuel used to be crude oil, coal or natural gas. Therefore the reduction in the emission of air pollutants is somewhat lower than for oil shale power plants. Wood or peat can be used only if the fuel is located closer to the boiler house than 50–100 km. In Estonia good prospects for wood and peat combustion are in the southern part of the country where smaller towns, extensive peat bogs and large forests are situated.

The possibilities to save energy in production, distribution and consumption are of increasing importance in Estonian economy. In 1997 the state resources to support the energy saving programme included 7 million EEK of investments and 1.7 million EEK of services.

Boiler house reconstruction for the World Bank loan was another important project during 1997. However, the share of private incentives in such of measures should increase in the future.

In energy saving also diminishing demand due to measures to improve energy efficiency in the buildings will also be of great importance. Adding a third glass to existing double glazed windows or replacement with new ones with three glasses, improvement of thermal insulation of external walls, installation of new insulated sloped roofs or insulation on flat roofs, replacement of old inefficient boilers with new and efficient ones, installation of new thermal substations in buildings etc. should be mentioned. If the effect of those methods could diminish energy consumption by 5%, their effect in the case of high CO_2 emission tax scenario will be 95 million kroons annually and 37 million kroons in low CO_2 tax scenario in 2010 due to a smaller amount of GHG emission. Those figures could be also compared with the amount of investments necessary for such improvements.

15 Conclusions

The actual development of the Estonian economy in recent years showed quite modest GDP growth in 1995 and 1996, but a sharp 11.4% increase in 1997. At that time energy consumption has remained stable. From today's perspective development according to the High Energy Demand scenario of the energy system seems to be the most probable for the near future. Actual changes and decisions will be affected by forthcoming privatisation of the power sector.

Oil shale will be still the most probable energy source for Estonia to be used in the nearest future. Therefore, the GHG mitigation options in the use of oil shale combustion technologies have a key role to play here. Presently high temperature pulverised firing technology (PF) is used in oil shale fired power plants in Estonia. The boilers used in power plants have been specially designed for Estonian oil shale. The PF technique for burning oil shale is characterised by very intensive fouling of the heat transfer surfaces of the boiler with ash deposits and high temperature corrosion. New approaches to combustion provide the main possibility to diminish the emission of GHG.

From the viewpoint of supply security and also national security, high dependence of the power and heating sector on natural gas (economically optimal under strict environmental restrictions and taxes) is not desirable until Estonia has only one gas supplier – Russia. An increase in the share of imported fuels in the energy balance, which is especially strong under mitigation scenarios, could be restricted by the negative influence on the balance of payments and foreign trade balance because the already high foreign trade and current account deficit would increase substantially.

So far only a small part of the available renewable energy sources are in use. In the longer perspective the government envisages an increase in the share of peat, wood and wind energy from the present 8% to 13% to year 2010. The substitution of some part of primary energy produced from oil shale with energy from renewable resources will be one of the main methods of the GHG mitigation.

The possibilities to save energy in production, distribution and consumption are of increasing importance in the Estonian economy. In energy saving also diminishing demand due to measures to improve energy efficiency in the buildings will be of great importance. Adding a third glass to the existing double glazed windows or replacement with new ones with three glasses, improvement of thermal insulation of external walls, installation of new insulated sloped roofs or insulation on flat roofs, replacement of old inefficient boilers with new and efficient ones, installation of new thermal substations in buildings are the main methods for diminishing energy use. The costs of those energy saving methods could be compared with the amount of investments necessary for such improvements. The evaluation of economic efficiency of the relevant projects should consider also possible indirect effects related to the GHG mitigation and additional potential costs that will occur in the economy if those energy saving methods are not applied.

The introduction of additional supportive financial schemes for increasing the amount and share of renewable energy sources in energy production should be one tool for the promotion of respective changes in the economy and could be seen as an important issue in the GHG mitigation proposals. Those financial schemes should cover tax exemptions for respective projects, direct subsidies for developing and introducing respective technologies.

The restructuring of Estonian energy system and increasing the share of renewable energy sources could be discussed also in the framework of regional development. The distribution of economic activities more uniformly between the regions could be supported by development of local energy production based on renewable energy sources. More uniform regional development is one of the political imperatives of Estonian future economic policy and so regional policy targets and wider use of renewable resources for energy production could support each other.

Conclusions

In Estonia power engineering is responsible for the bulk of GHG emissions. The most important component of GHG is CO_2 formed in the course of the combustion of fuels.

The energy sector policy is based on various acts, plans and agreements. The Government of Estonia has identified the development of the energy sector as a strategic component in the stable development of economy. In June 1997 the Riigikogu (the Parliament of Estonia) passed the Energy Act. In June 1998 conditions operating to the obligation to buy electricity generated as a result of harnessing renewable energy were added. The development trends of power engineering were approved in the Long Term Development Plan of the Fuel and Energy Sector adopted by the Riigikogu in February 1998.

The obligations of the Republic of Estonia in the field of environmental protection connected with the energy sector are fixed in the following agreements. The Kyoto Protocol on Global Climate Change, according to which Estonia will have to reduce the emission of CO_2 by at least 8% over the period 2008–2012 as compared with the 1990 level. The bilateral agreement on Long Range Transboundary Pollution was concluded between Estonia and Finland in June 1993. This obligates Estonia to reduce the emission of sulphur dioxide by the years 1997 and 2005 respectively by 50% and 80% as compared to the 1980 level and to keep nitrogen oxides on the levels not surpassing those of 1994. Up to the present Estonia has been in line with those requirements.

Estonia has considerable indigenous primary fuel resources – oil shale, peat and wood.

In 1996 the total consumption of primary energy was 226.3 PJ.

The energy supply system in Estonia consists mainly of thermal power plants and district heating boiler houses. The main source of primary energy is oil shale. Estonian resources of oil shale are substantial. The active resource of oil shale is 1.2–1.3 Gt and the passive resources amount at least to 4 Gt. In 1996 the production of oil shale was 14.7 Mt or 133.8 PJ. Its share in the energy balance of Estonia is about 60%. Major consumers of oil shale are oil shale fired power plants, which burnt 13.0 Mt of oil shale in 1996.

Approximately 99% of electric power in Estonia is generated by oil shale fired power plants (mainly by two high-capacity ones, the Baltic and the Estonian thermal power plants). In addition oil shale is used in processing factories to produce shale oil, to make cement clinker and, to some extent, directly to heat production.

As a result of drastic changes in the Estonian economy the total emission of GHG has decreased about 45% during the last seven years. The CO_2 emission from fossil fuels decreased from 37 Mt in 1990 to 21 Mt in 1996.

Of the total amount of CO_2 formed in Estonia in 1996 as a result of burning fossil fuels about 72% (15.2 Mt) came from use of oil shale. Consequently the oil shale fired power plants deserve greatest attention from the standpoint of the abatement of CO_2 and also sulphur dioxide emissions.

Estonian oil shale fired power plants are physically worn, but their technological backwardness is even worse. Their economic and environmental indicators fail to meet contemporary requirements. Their net thermal efficiency is low and the concentration of sulphur dioxide in the flue gas is high. The power plants fired with oil shale need inevitably either reconstruction or technological renovation. If the currently applied pulverised combustion technology remains in use it will not be possible to reduce the concentration of CO_2 in the flue gas. The emission of CO_2 may fall somewhat on the account of increasing the efficiency of a power plant thanks to lower specific energy consumption for producing a unit of electricity. To reduce the emission of sulphur dioxide to the level fixed in international agreements cleaning devices have to be installed to the existing boilers. However, such a solution is unacceptable because of the high price of the sulphur cleaning devices. Also, this would raise the operation and maintenance costs of the power plant. Moreover, the lifetime of new cleaning equipment will be considerably longer than that of the existing boilers.

The most suitable technology that could be applied instead of the present high-temperature pulverised combustion is low-temperature fluidised bed combustion (FBC) technology. In case of the FBC technology the sulphur dioxide present in the combustion products is totally captured by oil shale ash and no sulphur dioxide emission will occur.

Among the fluidised bed technologies the most suitable one is the pressurised fluidised bed combustion (PFBC) technique of oil shale. As compared to pulverised combustion, the net thermal efficiency of the power plant will increase from the current 0.27–0.29 to 0.43–0.46 in using of PFBC technology. In case of the PFBC technique the concentration of CO_2 in the combustion products will fall not only from the decrease of specific consumption of fuel for the production of a unit of electricity but also as a result of the peculiarities of oil shale combustion processes. Application of the PFBC technology would enable to reduce the power plant CO_2 emissions from the present level of 12.5 Mt/yr. to 7.0-7.5 Mt/yr. (if the output of electricity remains unchanged). Also the emission of nitrogen oxides will fall to some extent. The use of the PFBC technology for oil shale does not mean only a rise in the efficiency of energy conversion process and reduced CO_2 emission but also a notable rise in the reserves of oil shale as a domestic fuel.

Estonia is a northern country with annual average air temperature of 4-6°C. In addition, it is quite windy as well. For that reason the heating period in Estonia is long, lasting 8–9 months. One possibility for reducing CO_2 emission from the heating sector is to increase the co-generation of electricity and heat. Still the widespread erection of small-scale co-generation plants is limited by very low density of population and buildings outside the major towns.

Some reduction of CO_2 emission can be achieved also by more extensive use of peat (if considered as renewable) and biofuels. About 48% of Estonia's territory is covered with forest. It is possible to get 4–4.5 Mm^3 fuel from forests, which is equivalent to 26–30 PJ of primary energy. In 1996 the use of biofuels (mostly wood) as a renewable energy was 2.1 Mm^3, which accounted for about 10% of the production of primary fuels in Estonia. This figure is showing a clear tendency towards growth.

Peat fuel, including peat briquettes, makes up about 4% of primary fuels produced in Estonia. In 1996 a total of 0.53 Mt peat fuels was produced. Approximately 22% of the territory of Estonia is covered with mires. The reserves of peat are estimated at 2.4 Gt. The increment of peat on Estonian bogs is estimated at about 1 mm per year, which is equivalent to 0.8 Mt. As far as the consumption of peat does not surpass its increment, it should be regarded as a renewable energy.

Harnessing of wind energy can also reduce the emission of CO_2. Estonia has considerable wind energy resources, especially in coastal areas. As a maximum, about 0.3 TW·h of electricity could be produced annually without conflicting with other requirements. For this approximately 120 MW of wind turbines should be installed in regions with good wind conditions. The price of wind generated electricity will be rather high compared with relatively low price of electricity produced from oil shale due to high capital costs of wind turbines. This is presently the main obstacle to harnessing wind energy. The decision of the Riigikogu of June 1998 to amend the Estonian Energy Act with the obligation to buy wind generated electricity may help overcome this obstacle.

The resource of hydropower in Estonia is very small. Its more extensive use would not have much impact on the energy balance.

To handle the huge amount of data on the complex of energy, environment and economy, the MARKAL and MARKAL-MACRO models were used.

It was considered in modelling that GHG emissions can be reduced by changes in both supply and consumer sides of the energy system. Supply side GHG mitigation options for Estonia are new clean and efficient fossil conversion technologies, more extensive use of CHP, change of fuels, wider use of renewables, possible introduction of nuclear power, reduction of grid losses of heat and electricity. Those options are modelled in MARKAL by describing the technical, cost, availability and environmental data of the relevant technologies. The main consumer side mitigation option is energy conservation.

On the basis of MARKAL results the following main conclusions can be drawn:

Total Primary Energy Requirements will remain almost stable until 2005 and then grow very modestly due to substantial decoupling between economic output and demands for energy services, reinforced by increasingly efficient energy conversion systems. Under the base case conditions oil shale based power production will continue to be the major electricity supplier through reconstructed units of existing power plants. The amount of natural gas power (CHP, condensing combined cycle and gas turbines to meet the peak requirements) will increase significantly. On the long term, coal and nuclear power plants will offer the best prospects to give the base load electricity generation.

Using The Integrated Systems Approach to the modelling, the reduction of CO_2 is achieved due to changes in technology and fuel mix on both the supply and demand sides of the system. When CO_2 tax rises the following changes will take place in the system: the use of natural gas will increase; wood use will grow up to the sustainable limit; a nuclear power plant will be introduced; hydro and wind energy, high cost energy conservation measures, and even biomass CHP will become attractive.

When the CO_2 reduction possibilities were analysed using The Partial Solution Approach, the measures using natural gas as well as restoration of small hydro plants were not considered as specific options because they were extensively introduced already under the baseline scenario. The results show that most of the energy conservation measures should be implemented. The main problem here can be the arrangement of financing of those projects. Large amounts of CO_2 emissions could be cut by restricting electricity export and starting to import instead. This option still means that CO_2 could be emitted somewhere else and it will also affect the whole economy (state budget, foreign trade balance, energy prices etc.). Changes in electricity export-import should be regulated by market.

Estonian Energy Strategy, Long Term Development Plan for the Estonian Fuel and Energy Sector, and MARKAL baseline results all foresee the continuation of oil shale power engineering during a few decades, though not in the present volume. Considering that, reconstruction of existing power plants with transfer to PFBC is the most attractive option in the energy conversion sector for the reduction of CO_2, but also other emissions in the short term.

In the long run, GHG emissions could be radically reduced by introducing nuclear power. This option needs besides economic considerations also a well discussed political decision. Nuclear power is favoured only when the highest environmental taxes are considered.

Wind energy and small-scale biomass CHP along with some high cost conservation measures appear to be the most expensive measures of CO_2 reduction considered here.

The modelling of the Estonian energy system with the help of the MARKAL model shows a possibility to replace oil shale by natural gas. However, this result should be considered with utmost caution. Namely, Estonia buys natural gas presently only from Russia and if large amounts of gas are needed this would not allow Estonia to guarantee national security of energy supplies. In case of a monopolistic supply of gas its price may drastically rise when a certain amount is reached. Excessively big consumption of natural gas would have a negative effect on the national ratio of imports and exports. Giving up the use of oil shale, which is a domestic fuel, would mean that mines should be shut down. On the one hand this would mean large closing expenditures, on the other serious social and political problems would arise. It will be very expensive to reopen mines that have been closed. This would practically mean losing the energy resource of those mines.

We should not ignore the possibility of building a nuclear power plant in Estonia. The MARKAL model shows this on the basis of economic and environmental consideration. Presently the time is not yet ripe for making a decision. In the near future a relevant discussion based on scientific, economic, political etc. considerations should be opened, whereas emotions should not interfere with these discussions. It is most likely that this question will soon be on the agenda in the whole Baltic region. If no nuclear power plant is built in Estonia, it will be erected in some other country of the region. The existence of a nuclear power plant is undoubtedly an asset for the development of research and technology as it requires a highly educated staff. It is not possible to rely on the Ignalina nuclear power plant in Lithuania, which is physically and morally out of date and should be replaced in the near future.

In the demand side the most important CO_2 mitigation option is energy conservation. The main energy consumption in the Estonian residential sector goes for space and water heating. Energy conservation measures are connected with renovation of buildings. These measures fall into three groups. The first group includes the interventions concerning heat and hot water metering. The second are low cost investments such as sealing of cracks, gaps of window glasses, doors and frames, insulation of pipes, hydraulic balancing of the internal heat distribution system, repair of hot water system, installation of thermostatic valves on radiators, etc. The third group includes medium and high cost investments such as adding a third glass to windows, improvement of thermal insulation of external walls, additional insulation of roofs, improvement or replacement of existing boilers, etc. The total energy conservation potential in the residential sector is in the range 20–30% compared with the present energy consumption.

Reporting Forms

1 Fuel price assumptions

Base year = 1995

Country: Estonia

Table 1.1 basic assumptions	Base year	2010	2025
International (CIF) price of crude oil, US$/bbl	18	22,2	28
International (CIF) price of coal, US$/ton	50	50	50
Local price of fueloil(light), local currency/GJ	37	44,5	57,7
Local price of gasoil/diesel, local currency/GJ	35	44,5	57,7
Local price of natural gas, local currency/GJ	28,5	34	44
Local price of gasoline, local currency/GJ	50,46	62	80,35
Local price of coal, local currency/GJ	20	24,2	24,2
Local price of oil shale, local currency/GJ	8,25	17,7	21,17
Local price of peat, local currency/GJ	8,7	17,5	22

Table 1.2 sensitivity case	Base year	2010	2025
International (CIF) price of crude oil, US$/bbl			
International (CIF) price of coal, US$/ton			
Local price of fueloil, local currency/GJ			
Local price of gasoil/diesel, local currency/GJ			
Local price of natural gas, local currency/GJ			
Local price of gasoline, local currency/GJ			
Local price of coal, local currency/GJ			
Local price of fuel1, local currency/GJ			
Local price of fuel2, local currency/GJ			

2 Key national indicators

Country: Estonia

Table 2.1 GDP		Base year	2010	2025
Total	(fixed local prices)	MEEK		
Primary	Agriculture	2233,6		
	Forestry	534,1		
	Mining	601,3		
Secondary	Industry	6264,6		
	Construction	2115,9		
	Transport	3776,2		
Tertiary	Services	5456,5		

Table 2.2 National indicators	Base year	2010	2025
Population (millions)	1,48	1,44	1,44
Urban population (%)	70	70	70
Land cover (1000 km2)	45,2	45,2	45,2
Forest land (%) in baseline	47,7	47,7	47,7
Agricultural land (%) in baseline	25	25	25

3 Macroeconomic statistics

Country: Estonia

Table 3.1 GDP		MEEK	Base year
Consumption	Households		23752,2
	Government		9812,5
Investment			10576,4
Foreign trade	Exports		31279,6
	Imports		34653,2
Monetary	Inflation	%	28,9

Table 3.2 Labour force (thousands)		Base year
Primary	Agriculture	74,1
	Forestry	
	Mining	10,3
Secondary	Industry	157
	Construction	47,9
	Transport	55,4
Tertiary	Services	192,2
Unemployment		8,7

Table 3.3 Exchange rate		
Exchange rate of to Estonian Kroon		1 US$ = EEK
	1990	
	1991	
	1992	12,107
	1993	13,223
	1994	12,983
	1995	11,465
	1996	12,035

Table 3.4 Inflation rate	%
1996	14,8

4 Energy sector (a)

Country: Estonia

Table 4.1 (a) Total energy requirement (PJ)	Base year	2010	2025
Reference scenario total	228,84	204,21	227,46
OIL SHALE	138,58	54,68	55,65
Oil products	48,71	53,77	62,48
Natural gas	24,5	69,3	81,89
Coal products	0,57	1,11	1,66
Hydropower	0,04	0,04	1,47
Nuclear	0	0	0
WOOD	13,75	27,26	22,33
PEAT	5,43	3,51	10,16
EXPORT ELEC	-2,74	-5,46	-8,18

Table 4.2 (a) Total final energy by sector (PJ)	Base year	2010	2025
Reference scenario total	112,67	136,05	163,78
Industry	31,49	35,21	39,08
NON-ENERGY USE OF FUELS	8,45	8,45	8,45
Agriculture	3,84	2,92	3,00
Service	6,67	8,55	9,78
Residential	32,15	34,51	42,47
Transport	30,07	46,41	61,00

Table 4.3 (a) Electricity supply (GWh)	Base year	2010	2025
Reference scenario total	7981	9281	11172
Oil	8	375	0
Natural gas	8	4117	5281
Coal	0	0	0
HYDRO&WIND	3	3	156
Nuclear	0	0	0
CONV. OSH	7961	0	0
Oil shale (reconstr.)	0	4089	4472
PEAT CHP	0	181	747
WOOD (NEW PAPER CHP)	0	517	517
Net import	0	0	0

4 Energy sector (b)

Country: Estonia

Table 4.1 (a) Total energy requirement (PJ)	Base year	2010	2025
Low CO2 tax scenario total	228,85	191,51	225,41
OIL SHALE	138,58	25,00	45,89
Oil products	48,72	53,90	62,48
Natural gas	24,50	90,59	88,72
Coal products	0,57	0,72	1,66
Hydropower	0,04	0,26	1,47
Nuclear	0,00	0,00	0,00
WOOD	13,75	22,99	30,85
PEAT	5,43	3,51	2,52
EXPORT ELEC	-2,74	-5,46	-8,18

Table 4.2 (a) Total final energy by sector (PJ)	Base year	2010	2025
Low CO2 tax scenario total	112,67	136,05	163,78
Industry	31,49	35,21	39,08
NON-ENERGY USE OF FUELS	8,45	8,45	8,45
Agriculture	3,84	2,92	3,00
Service	6,67	8,55	9,78
Residential	32,15	34,51	42,47
Transport	30,07	46,41	61,00

Table 4.3 (a) Electricity supply (GWh)	Base year	2010	2025
Low CO2 tax scenario total	7981	9239	11169
Oil	8	375	0
Natural gas	8	6856	6767
Coal	0	0	0
HYDRO&WIND	3	28	156
Nuclear	0	0	0
CONV. OSH	7961	0	0
Oil shale (reconstr.)	0	1283	3550
PEAT CHP	0	181	181
WOOD (NEW PAPER CHP)	0	517	517
Net import			

Table 4.1 (a) Total energy requirement (PJ)	Base year	2010	2025
High CO2 tax scenario total	228,85	186,67	209,3
OIL SHALE	138,58	9,18	8,31
Oil products	48,72	53,90	62,48
Natural gas	24,50	96,64	107,18
Coal products	0,57	0,72	1,66
Hydropower	0,04	0,92	1,47
Nuclear	0,00	0,00	3,34
WOOD	13,75	27,26	31,99
PEAT	5,43	3,51	1,05
EXPORT ELEC	-2,74	-5,46	-8,18

Table 4.2 (a) Total final energy by sector (PJ)	Base year	2010	2025
High CO2 tax scenario total	112,67	136,05	163,78
Industry	31,49	35,21	39,08
NON-ENERGY USE OF FUELS	8,45	8,45	8,45
Agriculture	3,84	2,92	3,00
Service	6,67	8,55	9,78
Residential	32,15	34,51	42,47
Transport	30,07	46,41	61,00

Table 4.3 (a) Electricity supply (GWh)	Base year	2010	2025
High CO2 tax scenario total	7981	9239	11169
Oil	8	375	0
Natural gas	8	8064	9578
Coal	0	0	0
HYDRO&WIND	3	97	156
Nuclear	0	0	847
CONV. OSH	7961	0	0
Oil shale (reconstr.)	0	6	0
PEAT CHP	0	181	72
WOOD (NEW PAPER CHP)	0	517	517
Net import			

Table 4.1 (a) Total energy requirement (PJ)	Base year	2010	2025
All High taxes scenario total	228,83	187,61	206,96
OIL SHALE	138,58	11,87	9,23
Oil products	48,70	50,17	62,48
Natural gas	24,50	101,57	100,98
Coal products	0,57	0,72	1,66
Hydropower	0,04	0,92	1,47
Nuclear	0,00	0,00	7,44
WOOD	13,75	24,31	30,83
PEAT	5,43	3,51	1,05
EXPORT ELEC	-2,74	-5,46	-8,18

Table 4.2 (a) Total final energy by sector (PJ)	Base year	2010	2025
All High taxes scenario total	112,67	136,05	163,78
Industry	31,49	35,21	39,08
NON-ENERGY USE OF FUELS	8,45	8,45	8,45
Agriculture	3,84	2,92	3,00
Service	6,67	8,55	9,78
Residential	32,15	34,51	42,47
Transport	30,07	46,41	61,00

Table 4.3 (a) Electricity supply (GWh)	Base year	2010	2025
All High taxes scenario total	7981	9233	11169
Oil	8	3	0
Natural gas	8	8325	8444
Coal	0	0	0
HYDRO&WIND	3	97	156
Nuclear	0	0	1886
CONV. OSH	7961	0	0
Oil shale (reconstr.)	0	256	131
PEAT CHP	0	36	36
WOOD (NEW PAPER CHP)	0	517	517
Net import			

Table 4.1 (a) Total energy requirement (PJ)	Base year	2010	2025
Expensive oil shale scenario total	228,84	188,43	220,04
OIL SHALE	138,58	17,21	21,69
Oil products	48,71	53,90	62,48
Natural gas	24,50	95,13	89,72
Coal products	0,57	1,11	17,05
Hydropower	0,04	0,04	1,47
Nuclear	0,00	0,00	0,00
WOOD	13,75	22,99	21,79
PEAT	5,43	3,51	14,02
EXPORT ELEC	-2,74	-5,46	-8,18

Table 4.2 (a) Total final energy by sector (PJ)	Base year	2010	2025
Expensive oil shale scenario total	112,67	136,05	163,78
Industry	31,49	35,21	39,08
NON-ENERGY USE OF FUELS	8,45	8,45	8,45
Agriculture	3,84	2,92	3,00
Service	6,67	8,55	9,78
Residential	32,15	34,51	42,47
Transport	30,07	46,41	61,00

Table 4.3 (a) Electricity supply (GWh)	Base year	2010	2025
Expensive oil shale scenario total	7981	9239	11169
Oil	8	375	0
Natural gas	8	7589	6747
Coal	0	0	0
HYDRO&WIND	3	3	156
Nuclear	0	0	0
CONV. OSH	7961	0	0
Oil shale (reconstr.)	0	575	2717
PEAT CHP	0	181	1033
WOOD (NEW PAPER CHP)	0	517	517
Net import			

5 GHG emissions (million tonnes)

Country: Estonia

Table 5.1 (a) Reference scenario emissions	Base year	2010	2025
Reference scenario total CO_2	20,847	14,392	16,513
CO_2 from fossil fuels			
CO_2 from decrease of biomass stock			
CO_2 from cement & lime			
Reference scenario total CH_4			
CH_4 from combustion			
CH_4 from oil and gas sector			
CH_4 from coal mining			
CH_4 from enteric fermentation			
CH_4 from landfills/sewage treatment			
CH_4 from rice production			
CH_4 from forest and savannah burning			
Reference scenario total N_2O	0,048	0,037	0,037
N_2O from combustion			
N_2O from agricultural soils			

Table 5.1 (b) Mitigation scenario emissions	Base year	2010	2025
Mitigation scenario total CO_2			
Low CO_2 tax	20,84657	12,41237	15,02061
High CO_2 tax	20,84657	10,95606	11,01448
All High taxes	20,84657	11,33526	11,64587
Expensive oil shale	20,84657	11,86070	15,19199
CO_2 from fossil fuels			
CO_2 from decrease of biomass stock			
CO_2 from cement & lime			
Mitigation scenario total CH_4			
CH_4 from combustion			
CH_4 from oil and gas sector			
CH_4 from coal mining			
CH_4 from enteric fermentation			
CH_4 from landfills/sewage treatment			
CH_4 from rice production			
CH_4 from forest and savannah burning			
Mitigation scenario total N_2O			
Low CO_2 tax	0,048	0,038	0,037
High CO_2 tax	0,048	0,038	0,038
All High taxes	0,048	0,037	0,037
Expensive oil shale	0,048	0,038	0,039
N_2O from combustion			
N_2O from agricultural soils			

6 Cost curve data

Country: Estonia

Table 6.1 Short term cost curve, 2010	reduction (1000 tonnes GHG)			local currency/ton-	US$/ton-
CO2 mitigation option	CO2	CH4	N2O	CO2 equivalent	CO2 equivalent
1 CONS4	48			-1403	-116
2 CONS2	75			-1254	-104
3 CONS8	54			-1055	-87
4 CONS3	45			-970	-80
5 CONS1	60			-475	-39
6 CONS6	34			-149	-12
7 ELIMP L	312			30	2
8 ELIMP H	312			82	7
9 PFBC	641			133	11
10 ELEXP	1238			230	19
11 CONS7	54			274	23
12 CONS5	94			625	52
13 WIND L	22			1521	126
14 BIOCHP	29			1789	148
Total reduction	3018				
Total reference scenario emissions	14392				

Table 6.2 Long term cost curve, 2025	reduction (1000 tonnes GHG)			local currency/ton-	US$/ton-
CO2 mitigation option	CO2	CH4	N2O	CO2 equivalent	CO2 equivalent
1 CONS2	119			-1454	-120
2 CONS8	71			-1269	-105
3 CONS1	94			-629	-52
4 ELIMP L	745			16	1
5 ELIMP H	745			70	6
6 PFBC	1317			73	6
7 CONS7	71			172	14
8 NUCLEAR	4461			177	15
9 BIOCHP	552			227	19
10 ELEXP	1491			301	25
11 WIND L	166			425	35
12 WIND L+S	999			518	43
Total reduction	10831				
Total reference scenario emissions	16513				

Please list the options after increasing marginal cost!

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