

THESIS ON MECHANICAL ENGINEERING E75

**Methodology for Calculating
CO₂ Emission from
Estonian Shale Oil Industry**

INGE ROOS

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Declaration:

Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

Inge Roos

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MEHCHANOTEHNIKA E75

CO₂ emissiooni arvutusmeetod Eesti põlevkiviõlitööstusele

INGE ROOS

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LIST OF ORIGINAL PUBLICATIONS

- Paper I Roos, I., Soosaar, S., Volkova, A., Streimikene, D. Greenhouse gas emission reduction perspectives in the Baltic States in frames of EU energy and climate policy. *Renewable and Sustainable Energy Reviews*, 2012, Vol. 16, pp. 2133–2146.
- Paper II Volkova, A., Roos, I., Soosaar, S., Siirde, A. Competitiveness of wood fuel in the conditions of open electricity market in Post-Kyoto period: Case study for Estonia. *Proceedings of 3rd International Conference on Clean Electrical Power: Renewable Energy Resources Impact*. IEEE, Ischia, Italy, 2011, 14th-16th June, pp. 600–667.
- Paper III Siirde, A., Roos, I., Martins, A. Estimation of carbon emission factors for the Estonian shale oil industry. *Oil Shale*, 2011, Vol. 28, No. 1s, pp. 127–139.

Author's Contribution to the Publications

The author's contribution to the papers included in the thesis is following:

- Paper I The main author of the paper. The author planned and carried out data collection and calculations. She interpreted the results and wrote the majority of the manuscript.
- Paper II The author participated in planning of the paper. She interpreted the results and wrote the majority of the manuscript.
- Paper III The main author of the paper. The author planned and carried out data collection and calculations. She interpreted the results and wrote the majority of the manuscript.

INTRODUCTION

Estonia is the only country in the world using oil shale as its major primary source of energy. In 2010, the share of energy from oil shale has been about 69 percent of the primary energy supply [1]. The share of oil shale (including secondary fuels made from oil shale: shale oil and shale gas) in electricity production is even larger, totalling about 89 percent of the electricity production in 2010. Oil shale as a local energy source plays an important role in the guaranteed energy supply and energy independency not only for Estonia, but for the whole Baltic region. Nevertheless, oil shale energy is also the main source of greenhouse gases.

In 2010, the energy sector contributed about 88.6 percent of the total greenhouse gas emissions, totalling 18.19 Mt CO₂ equivalent. The substantial amount of energy related emissions is caused by extensive consumption of fossil fuels for electricity and heat production. The share of oil shale, shale oil and shale gas combustion was about 73 percent of the energy sector total GHG emissions¹ [2].

In December 2008, the European Parliament adopted a set of legislative documents (the so called EU climate and energy package) for transforming Europe gradually into a low-carbon economy and increasing energy supply security. An agreement has been reached on legally binding targets, by 2020: to cut GHG emissions by 20% compared to 1990; to establish a 20% share for renewable energy in final energy consumption and the share of biofuels up to 10% in transport fuels, and to achieve a 20% reduction in energy consumption by 2020 by improving energy efficiency. Regarding the reduction of GHG emissions, the package contains an offer to go further and commit to a 30% cut in the event of a satisfactory international agreement being reached [3].

To reach these targets Estonia has to find a solution for reducing CO₂ emissions from energy sector, which could be achieved by reducing the high share of oil shale in energy production – using more renewables or fuels with lower carbon content and by improving the energy efficiency introducing new combustion and energy conversion technologies.

Because oil shale as a strategically important fuel for Estonia will play an important role in electricity generation also in the near future, many scientific studies have been dedicated to investigating the opportunities of increasing the efficiency of oil shale combustion, which include introduction of new combustion technologies (e.g., fluidized bed combustion instead of pulverized combustion), combustion of enriched oil shale in fluidized bed boilers, etc., which is also accompanied by the reduction of CO₂ emissions [4–10].

¹ According to the UNFCCC reporting guidelines anthropogenic GHG sources for energy sector are fossil fuel combustion in energy industries, manufacturing, transport and other sectors (commercial, residential and agriculture).

However, the greenhouse gas emissions from thermal processing of oil shale have been less studied and there are no standard methods for their calculation available.

Shale oil production in Estonia is unique in Europe with a long-term tradition industry, which makes a significant contribution to the national economy. 85% of the oil production is exported to the EU countries. In 2010, the shale oil exports accounted for 1.8%² of the total exports from Estonia.

Shale oil production has gained importance in the light of higher oil prices, declining petroleum supplies and rapidly increasing demand from emerging economies. Shale oil is used as admixture to marine fuels, as well as a fuel in boilers and industrial furnaces. The advantage of shale oil compared to heavy fuel oil is its lower viscosity, low sulphur content and freezing point.

Objectives of the thesis

Objectives of the thesis are:

- To work out a comprehensive methodology and calculation tool for the estimation of greenhouse gas emissions from thermal processing of oil shale in order to improve the quality and reliability of the national greenhouse gas inventory methodology.
- To analyse the possibilities of greenhouse gas emission reduction of the Estonian energy sector in frames of EU energy and climate policy.

In order to estimate the level of GHG emissions in the future, and assess the reduction potential the current GHG calculation methodology has to be improved. Estonia has developed the country specific carbon emission factors for pulverized combustion and fluidized bed combustion of oil shale [4], but there are no carbon emission factors for the products and co-products of oil shale thermal processing (pyrolysis).

Approval of the results

The results of this work were presented at an international conference:

- The 3rd International Conference on Clean Electrical Power, Renewable Energy Resources Impact. IEEE, Ischia, Italy, 2011, 14th–16th June.

and in scientific journals:

- Renewable and Sustainable Energy Reviews, 2012, Vol. 16.
- Oil Shale, 2011, Vol. 28, No. 1s.

² *Statistics Estonia, www.stat.ee*

Novelty

The novelty of the work lies in the developed new methodology for the technology specific CO₂ emission calculation based on the balance of carbon containing mass flows. Additionally, the methodology enables to determine the quantity of carbon stored in products and residues from the Estonian oil shale thermal processing industry.

The calculation methodology allows on the basis of incomplete data to calculate the carbon emission factors for oil shale entering the pyrolysis process as well as for the process outputs (oil, gas, solid residues and flue gas). The methodology uses calculation formulas from the earlier research carried out by the Department of Thermal Engineering of the Tallinn University of Technology.

ABBREVIATIONS AND SYMBOLS

Abbreviations

ΔGHG	difference between emissions from the oil shale combustion and the wood combustion
AD	activity data
AFC	aerofountain combustor
AFD	aerofountain dryer
CHP	electricity and heat cogeneration
CO ₂	carbon dioxide
ETS	emission trading system
GDP	Gross Domestic Product
GHC	gaseous heat carrier
GHG	greenhouse gas
GHG _{os}	specific GHG emission factor per produced electricity unit for oil shale, tCO ₂ /MWh _{el}
GHG _{wood}	specific GHG emission factor per produced electricity unit for the wood based electricity production, tCO ₂ /MWh _{el}
ICP	<i>in-situ</i> conversion process
NCV	net calorific value
NO	not occur
SHC	solid heat carrier
UNFCCC	United Nations Framework Convention on Climate Change

Symbols

A_{ash}	content of ash in solid heat carrier, %
A_{os}^d	ash content in dry oil shale, %
A_{os}^r	ash content in oil shale as received, %
B_{fg}	flue gas production, Nm ³
B_{gg}	generator gas production, Nm ³
B_{os}	oil shale consumption, t
B_{pg}	pyrolysis gasoline production, t
B_{so}	shale oil production, t

B_{scg}	semi-coke gas production, Nm ³
B'_{gg}	generator gas production, TJ
B'_{os}	oil shale consumption, TJ
B'_{scg}	semi-coke gas production, TJ
B'_{so}	shale oil production, TJ
B'_{pg}	pyrolysis gasoline production, TJ
C_{ash}	amount of carbon leaving the process with ash, t
C_{fg}	amount of carbon leaving the process with flue gas, t
C_{gg}	amount of carbon leaving the process with generator gas, t
C_{os}	amount of carbon in oil shale entering the process, t
C_{pg}	amount of carbon leaving the process with pyrolysis gasoline, t
C_{sc}	amount of carbon leaving the process with semi-coke, t
C_{scg}	amount of carbon leaving the process with semi-coke gas, t
C_{so}	amount of carbon leaving the process with shale oil, t
C_{os}^d	carbon content of oil shale dry matter, %
C_{os}^r	carbon content of oil shale as received, %
$(CO_2)_M^d$	content of mineral CO ₂ in oil shale dry matter, %
$(CO_2)_M^r$	content of mineral CO ₂ in oil shale as received, %
$(CO_2)_{ash}^d$	content of mineral CO ₂ in dry heat carrier from AFC, %
FeS_2	FeS ₂ content in sandy-clay part of oil shale, %
FeS_2^d	content of pyrites in dry oil shale, %
k_i	share of wood used in cogeneration plant i , %
k_j	share of wood used in cogeneration plant j , %
k_{os}	share of wood used in oil shale plants, %
k_{CO_2}	decomposition rate of carbonate minerals in semi-coke
m_s	increase of ash amount because of sulphur binding
$M(C)$	molar mass of C
$M(CO_2)$	molar mass of CO ₂
S_p^d	content of pyritic (marcasite) sulphur in dry oil shale, %
P^r	content of apparent combustible matter in oil shale as received, %
P_{wood}	installed capacity for electricity production from wood, MW _{el}
P_{CHPi}	installed capacity of existing cogeneration plant i , MW _{el}
P_{os}	installed capacity of oil shale units, MW _{el}

$q_{c\ gg}$	carbon emission factor of generator gas, tC/TJ
$q_{c\ os}$	carbon emission factor of oil shale, tC/TJ
$q_{c\ pg}$	carbon emission factor of pyrolysis gasoline, tC/TJ
$q_{c\ scg}$	carbon emission factor of semi-coke gas, tC/TJ
$q_{c\ so}$	carbon emission factor of shale oil, tC/TJ
$q_{CO_2\ gg}$	CO ₂ emission factor of generator gas, tCO ₂ /TJ
$q_{CO_2\ pg}$	CO ₂ emission factor of pyrolysis gasoline, tCO ₂ /TJ
$q_{CO_2\ os}$	CO ₂ emission factor of oil shale, tCO ₂ /TJ
$q_{CO_2\ so}$	CO ₂ emission factor of shale oil, tCO ₂ /TJ
$q_{CO_2\ scg}$	CO ₂ emission factor of semi-coke gas, tCO ₂ /TJ
$q_{CO_2/t}$	specific CO ₂ emission factor per unit of produced oil, tCO ₂ /t
Q_c	heating value of carbon, MJ/kg
Q_{gg}	lower heating value of generator gas, MJ/Nm ³
Q_{pg}	lower heating value of pyrolysis gasoline, MJ/kg
Q_{scg}	lower heating value of semi-coke gas, MJ/Nm ³
Q_{so}	lower heating value of shale oil, MJ/kg
Q_{os}^d	lower heating value of oil shale dry matter, MJ/kg
Q_{os}^r	lower heating value of oil shale as received, MJ/kg
Q'_{os}	corrected lower heating value of oil shale, MJ/kg
R^d	content of organic part in dry oil shale, %
t	operating time, h
T	industrial oil yield, %
T_L	laboratory oil yield, %
T^d	content of sandy-clay part in dry oil shale, %
T^r	content of sandy-clay part in oil shale as received, %
W_{os}^r	moisture content of oil shale as received, %
W_{wood}	electricity produced from wood per year, GWh
α	excess air factor
η	energy efficiency of oil shale thermal processing, %
ρ_{scg}	relative density of semi-coke gas, kg/Nm ³
ρ_{gg}	relative density of generator gas, kg/Nm ³

1. LITERATURE OVERVIEW

In Estonia, the major part of anthropological emissions of greenhouse gases originates from the energy sector, where the main fuel, especially in power generation, is oil shale. Oil shale compared with other fossil fuels has the low heating value, higher CO₂ emission factor and a large amount of solid residues going to landfill as well as other environmental hazards.

In 2010, the share of energy from oil shale provided about 69 percent of the primary energy supply [2]. In electricity production the share of oil shale, including secondary fuels made from oil shale (oil and gas) is even larger, totalling about 89 percent of the electricity production in 2010 [2]. Oil shale as a local energy source plays an important role in the guaranteed energy supply and energy independence not only for Estonia, but for the whole Baltic region. Nevertheless, oil shale energy is also the main source of greenhouse gases.

In 2010, the energy sector contributed 88.6 percent of total greenhouse gas emissions in Estonia, totalling 18.19 Mt of CO₂ equivalents. The substantial amount of energy related emissions, 80.4 percent is caused by extensive consumption of fossil fuels for power and heat production. In 2010, more than 90 percent of electricity production was still oil shale based contributing about 75 percent of the energy sector's greenhouse gas emissions [2].

Despite all the progress made in reducing the environmental impact of oil shale burning: introduction of new combustion technologies (fluidized bed combustion vs. pulverized combustion), combustion of enriched oil shale in fluidized bed boilers, etc., oil shale use for electricity production in the long term is not sustainable and there is the need to find new solutions to reduce the share of oil shale in the fuel balance.

In the National Development Plan for the Utilization of Oil Shale 2008–2015 the maximum limit of oil shale mining is set to 20 million tons a year. In implementing the plan, the objective in the long run is to achieve the maximum annual limit of oil shale mining of 15 million tons by the year 2015. At present, there are plans to decrease the share of oil shale use for electricity generation and on the other hand to increase the use of oil shale for thermal processing [11].

1.1 Oil shale

Oil shale is a sedimentary fossil mineral, which always consists of organic and inorganic components. The share of oil shale organic matter ranges from 10 to 70% [4]. The inorganic or mineral part consists of various rocks, of which from the technological aspect, the most important are carbonate part or limestone (as a potential source of additional CO₂) and pyrites (due to the sulphur content). The organic part of oil shale can be divided into two parts: bitumen – soluble in organic solvents (1–2%, sometimes up to 10%) and kerogen – a three-dimensional macromolecular system, which is insoluble in organic solvents [12].

The data on the chemical and mineralogical composition of oil shale components are based upon references [13, 14, and 15] and presented in Table 1.1.

Table 1.1 Chemical composition of Estonian oil shale (dry basis), %

Organic part		Mineral part			
		Sandy-clay part		Carbonate part	
Component	Content	Component	Content	Component	Content
C	77.45	SiO ₂	59.8	CaO	48.1
H	9.70	CaO	0.7	MgO	6.6
O	10.01	Al ₂ O ₃	16.1	FeO	0.2
N	0.33	Fe ₂ O ₃	2.8	CO ₂	45.1
S	1.76	TiO ₂	0.7		
Cl	0.75	MgO	0.4		
		Na ₂ O	0.8		
		K ₂ O	6.3		
		FeS ₂	9.3		
		SO ₃	0.5		
		H ₂ O	2.6		

The main characteristics of the organic matter of oil shale are: high hydrogen (9.7%), oxygen (10.01%) and low nitrogen (0.33%) content. The carbon hydrogen mass ratio C/H is 8, which is similar to liquid fuels. An important characteristic of the oil shale organic matter is also the high chlorine content [16].

The mineral matter of oil shale can be divided into two large groups: a sandy-clay or terrigenous part and a carbonate part. The sandy-clay part is densely intertwined with the organic matter of oil shale, considered as an inherent mineral impurity. The carbonate minerals in an oil shale deposit occur as separate layers. The carbonate part can be considered extraneous mineral matter [16].

1.2 Estonian shale oil industry

Estonia is the biggest shale oil producer in Europe and one of four countries in the world (among Russia, Brazil and China) commercially producing shale oil. There is some use and production of shale oil also in Austria and Germany for the medicine and cosmetics industry, but the quantities there are not comparable, either with the industrial production or use of shale oil in Estonia. The shale oil production in Estonia has become an important industry with long-standing traditions that has made a significant contribution to the national economy.

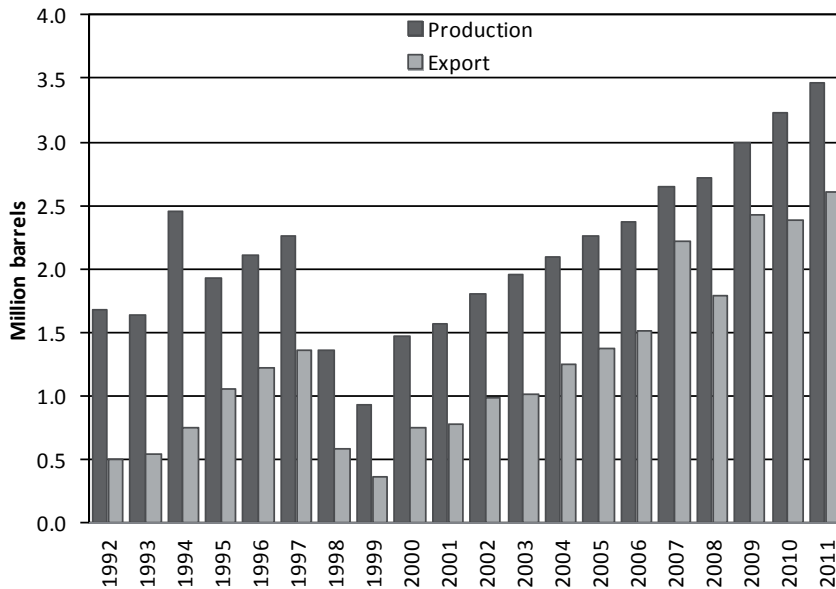


Figure 1.1 Shale oil production and export in Estonia 1992–2011, million bbl3 [1]

In Figure 1.1 the Estonian shale oil production and export in 1990–2011 is presented. From 2003 onwards, the shale oil production has increased steadily as a result of increased export opportunities, and with the addition of oil plant production units.

The share of shale oil export has also increased from year to year. When in 1992 it accounted for 30%, by 2008 the share of export had risen to 81 percent from the total oil production.

The shale oil production has gained importance in the light of higher oil prices, declining petroleum supplies, energy supply and security as well as rapidly increasing demand from emerging economies. Shale oil is used as an admixture to marine fuels, and as a fuel in boilers and industrial furnaces. The advantage of shale oil compared to heavy fuel oil is its lower viscosity, low sulphur content (1–2%) and freezing point.

The term ‘shale oil’ refers to any synthetic oil obtained by destructive retorting of oil shale. During the extraction process, the stable organic matter embedded in oil shale is thermally cracked and converted into oil, combustible gases, a solid ash and semi-coke. The composition of shale oil depends on the used extraction technology, composition of kerogen and presence of non-organic components such as sulphur, phosphate or nitrates.

³ 1 oil barrel = 158.987 litres

1.3 Theoretical background of oil shale thermal processing

1.3.1 Thermal processing of oil shale

The main parts of oil shale organic matter are various carbon chains, which, according to their origin, contain, in addition to organic carbon also hydrogen, sulphur, nitrogen and oxygen atoms. For the practical use of the oil shale organic content, for example, for the production of liquid fuels, it is necessary to break down the three-dimensional insoluble structure. One option is to heat oil shale to the temperature of 500–540 °C without oxygen access (known also as pyrolysis) [12].

During thermal decomposition of oil shale in pyrolysis process, in the oxygen-free conditions at a temperature between 480–500 °C, oil and gas as volatile compounds of oil shale processing products, and pyrogenetic water are formed. Their quantities and chemical nature depend on the composition of the organic mass of the fuel. The Estonian oil shale – kukersite – contains 30–40% of organic matter [17].

An important factor in the formation of volatile pyrolysis products is the hydrogen to carbon ratio of the organic matter in the fuel. The higher the ratio of H/C, the closer the organic fraction of solid fuel in its composition to crude oil is, and the higher is the yield of oil by thermal decomposition of the fuel. An important characteristic of oil shale organic matter is the initial temperature of thermal decomposition.

This is dependent on the composition and structure of the organic matter, but is also influenced by the heating rate. The initial temperature of thermal decomposition is influenced by the oxygen content in the fuel organic matter. The higher the oxygen content, the lower the starting temperature of thermal decomposition will be [15].

At the oil shale pyrolysis temperature of 100–105 °C, separation of mechanically bound water takes place. It is the water that has run into oil shale during mining. The first signs of the organic fraction decomposition appear already at 150 °C.

At the temperature of 170–180 °C the so-called oxidized gases are emitted, which form a negligible share per mass of oil shale. In the temperature range of 270–290 °C the formation of pyrogenetic water from hydrogen and oxygen in the oil shale organic matter begins. In the temperature range of 300–350 °C the release of light gas and oil fractions from kerogen begins. The major part of kerogen moves to the semi-fluid thermo bitumen phase, which during further heating decomposes into oil and gas. At the temperature of 450–500 °C the process ends and there remains a solid residue with the low C/H ratio – semi-coke. The oil yield of oil shale pyrolysis in an externally heated standard retort (if heated to a temperature of 520 °C) is about 65–67% by weight of oil shale organic matter. The rest of pyrolysis products are: gas 13–14%, pyrogenetic water 5%, and semi-coke 15–17% [18]. The stages of oil shale

thermal decomposition process with the corresponding temperature ranges are given in Figure 1.2.

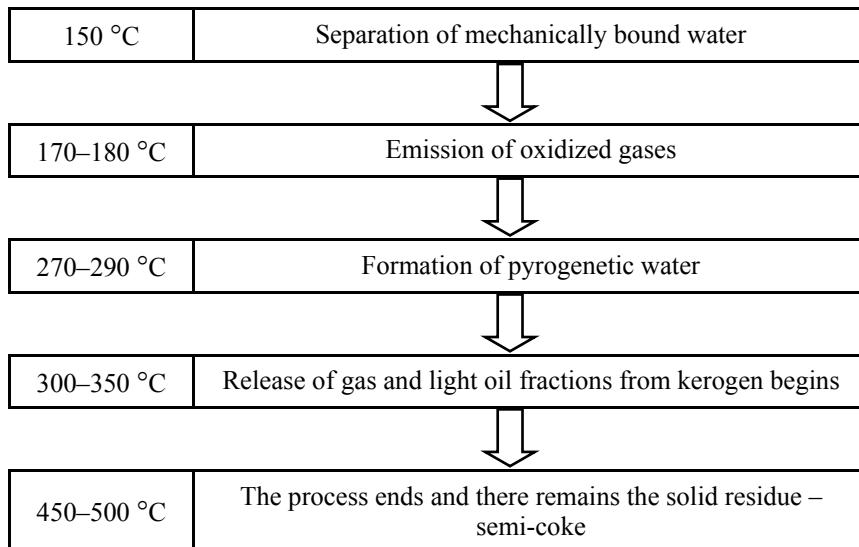


Figure 1.2 The stages of oil shale thermal decomposition with the corresponding temperature ranges

1.3.2 Technologies of oil shale thermal processing

There are several different shale oil production technologies in use in the world. By the manufacturing method of heat carrier the direct and indirect pyrolysis can be defined. The heat required for direct pyrolysis is obtained by burning oil shale residual carbon.

The combustion products of generator gas formed during the process ensure the pyrolysis process running due to their intrinsic heat content. In the direct pyrolysis the flue gas mixes with the generator gas, diluting it and lowering its heating value.

In the case of indirect pyrolysis the heat is produced by combustion of semi-coke (residual carbon) in a separate furnace. The flue gas does not mix with the pyrolysis gas and as a result high-calorific semi-coke gas as a co-product of the pyrolysis process is formed.

In general, the oil shale processing technologies can be broadly divided into two categories: above-ground and underground (*in-situ*) pyrolysis technologies.

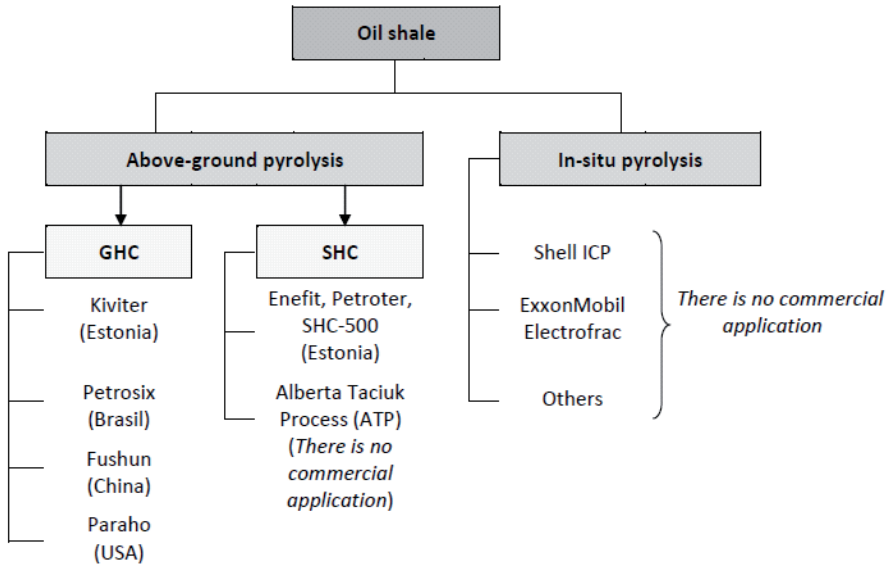


Figure 1.3 Oil shale thermal processing technologies

Underground pyrolysis technologies (in-situ)

Underground pyrolysis is a promising technology for deep and a thick (hundreds of metres) shale layers. Presently, there are only some pilot plants in operation, but no commercial shale oil production based on in-situ technology is in use. The above-ground and underground retorting do not compete, but rather complement each other. The advantages of the in-situ process are: the lack of mining, large volumes of production, and disadvantages: difficult process controllability, environmental issues (groundwater), high energy consumption, and resource loss – some of the carbon remains in the ground.

The Shell in-situ conversion process (ICP) process

In the ICP process the oil shale layers are surrounded by a freeze wall, which is usually formed from cooling pipes filled with liquid coolant to isolate the processing area from the surrounding groundwater and avoid draining of pyrolysis products. Electrical heaters are installed in the wells. Heating runs up to 2–3 years until the temperature reaches 340–370 °C. The formed oil is pumped into collection wells and diverted to the refinement plant. The pilot plant of Shell ICP technology is in operation in the United States, Colorado, where the oil shale layers are up to 600 metres thick and located at depths up to 500 metres [19]. In comparison, the thickness of Estonian oil shale layers is only 2–3 metres.

The above-ground process

According to the type of heat carrier, the existing above-ground industrial technologies can be divided into gaseous and solid technologies. A number of units

with very different operation principles are in the development phase now: using microwaves, plasma, etc. The main problem with most of the new developments is the high energy consumption.

Retorting technology with gaseous heat carrier – Paraho process

Paraho process (developed in the USA, Colorado) can be operated in two different heating modes, which are either direct or indirect. The Paraho direct process evolved from the gas combustion retort technology and is classified as an internal combustion method. Accordingly, the Paraho direct retort is a vertical shaft retort similar to the one used by Kiviter (Estonia) and Fushun (China) technologies [10]. The Paraho indirect process is classified as an externally generated hot gas technology. The Paraho indirect retort configuration is similar to the Paraho direct one except that a part of the gas from the compressor is heated to 600 °C–800 °C in a separate furnace and injected into the retort instead of air. No combustion occurs in the Paraho indirect retort itself. As a result, the fuel gas from the Paraho indirect retort is not diluted with combustion gases and the char remains with the disposed spent shale [20]. The main advantage of the Paraho process is simplicity in process and design; it has few moving parts and therefore, the construction and operating costs are low compared with more sophisticated technologies. The Paraho retort consumes no water, which is especially important for oil shale extraction in areas with water scarcity. A disadvantage common to both the Paraho direct and indirect technologies is that neither is able to process oil shale particles smaller than about 12 mm.

Retorting technology with gaseous heat carrier – Petrosix

Currently, Petrosix is one of four technologies of shale oil extraction in commercial use [21]. The Petrosix process was developed by the Brazil oil company Petrobras, which is one of the biggest oil companies in the world. The Petrosix technology was tailored for Irati oil shale, but it is possible to process other oil shales too. A pilot and demonstration unit was built in 1982 (65 t/h) followed by the construction of an industrial unit, which has been in successful commercial operation since 1991. The Petrosix process uses oil shale particles with the size between 6–50 mm. The company is actively involved in introducing the process worldwide – Jordan, the U.S., Morocco, etc. The advantages of the process are its simplicity and reliability. The disadvantages include: no oil shale particles smaller than 12 mm can be processed in the Petrosix retort, the process requires a large amount of water and plenty of semi-coke is formed.

Retorting technology with gaseous heat carrier – Fushun

The Fushun technology was developed and utilized for the extraction of shale oil in China during the mid-1920s. The commercial-scale utilization of the process began in 1930. In 2005, China became the largest shale oil producer in the world.

The advantages of the Fushun technology include low investment costs and stable operation. The process is characterized by the high thermal efficiency, but due to

the addition of air into the retort, the nitrogen dilutes the pyrolysis gas. In addition, the excess oxygen in retort burns out a part of produced shale oil, reducing the shale oil yield. The oil yield of the Fushun retort accounts for about 65% of the Fischer Assay. A disadvantage of this process is the high water consumption amounting to 6–7 units of water per unit of produced shale oil, and huge quantities of waste shale. It is not suitable for oil shale with small particle size and oil content lower than 5% [21].

Solid Heat Carriers (Galoter, Enefit, Petroter, SHC–500)

The solid heat carrier process is the "new generation" pyrolysis technology. Its main advantages are: utilization of all the mined oil shale resource (particle size 0–25 mm), maximum utilization of the energy potential of oil shale as hot ash from the process is used as a heat carrier and no semi-coke is formed. The only industrial oil shale processing units with solid heat carrier are operating in Estonia.

Alberta Taciuk process with Solid Heat Carrier (ATP)

In Canada the Alberta Taciuk Process (ATP) has been developed, but up to now it has no industrial application (pilot plant). In 1997–2004, efforts were made to use the ATP process in Australia. As a result, a pilot plant (6000 t/day) was built there. In 2004, the plant was shut down due to various reasons: environmental problems, low price of crude oil, design faults and high project cost – 300 million USD. The process was considered too complicated to cope with the changing oil shale characteristics, difficult access to different nodes and expensive materials [21].

1.3.3 Thermal processing technologies of oil shale in Estonia

In Estonia, thermal processing of oil shale has always been a part of a larger energy and chemical industry complex, not a separate entity. So far, the conversion of raw shale oil into oil products has mainly been a part of the same complex. At the same time, the crude shale oil can also be processed outside the thermal treatment complex, which can provide a basis for a specific oil shale chemical industry [12].

In the current work, the oil shale thermal processing technologies are classified by the type of heat carrier. There are two different oil shale thermal processing technologies applied in Estonia today. The Kiviter type gas generators or gaseous heat carrier (GHC) technology is in use by *VKG Oil AS* and in *Kiviõli Keemiatööstuse OÜ* (Kiviõli Oil Plant). The solid heat carrier technology (SHC, called also Galoter technology), carries different brand names – Enefit 140 in the *Eesti Energia Õlitehas AS* (Narva Oil Plant) and Petroter in *VKG Oil AS*.

In Figure 1.4 the oil shale thermal processing plants are presented by technology and their share in the total oil output in 2010.

Eesti Energia Õlitehas AS 34%	<ul style="list-style-type: none"> • Enefit-140 (SHC) • Enefit-280 (SHC, since 2013)
AS VKG Oil 54%	<ul style="list-style-type: none"> • Petroter (SHC) • Kiviter (GHC)
Kiviõli Keemiatööstus OÜ 12%	<ul style="list-style-type: none"> • Galoter-500 (SHC) • Kiviter (GHC)

Figure 1.4 Oil shale thermal processing plants by the technology used in Estonia in 2010

A detailed overview of the solid heat carrier unit is provided by N. Golubev [22] and that of gas generator unit by S. Doilov and J. Soone [23]. The current work gives a brief overview of these two oil shale processing technologies.

1.3.3.1 Gas heat carrier technology

The simplified layout of oil shale retorting in vertical gas generator is given in Figure 1.5 [24]. Oil shale processing in the vertical Kiviter type internal combustion retort (a gas generator) with the gaseous heat carrier is a universal technology suitable for retorting high-calorific (12 MJ/kg) lump oil shale with the particle size of 25–125 mm. The vertical retort is a metal vessel with inside refractory brick lining. The oil shale loading device (F), semi-coke unloading device (E) and extractor are arranged on the top and in the lower part of the retort vessel, respectively. Thermal processing of oil shale is carried out in the retorting chamber (C) in the cross flow of gaseous heat carrier (the combustion products of generator gas). The hot gases heat up and dry oil shale and after reaching the required temperature for retorting (450–550 °C), the organic matter of oil shale starts to decompose. The mixture of the heat carrier, oil and water vapour flows into the collector chamber (G) while the semi-coke (retorted oil shale) moves downward to the cooling chamber (D). The oil vapour and gas are discharged from the retort to the oil separation system (H) via the outlet connections. Some of the discharged generator gas is burned in the combustion chamber of the retort (A) for producing a gaseous heat carrier. The most of the produced generator gas is directed into the power plant boilers for firing.

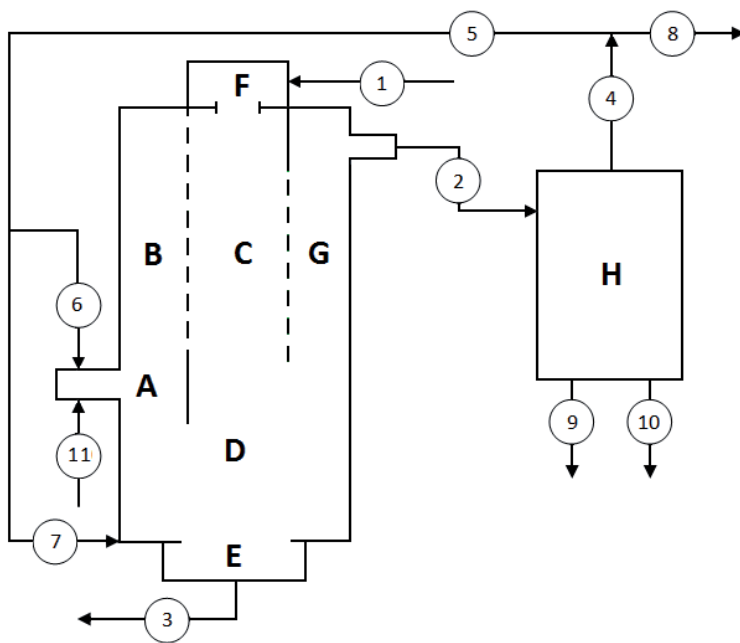


Figure 1.5. Principal layout of oil shale pyrolysis in the vertical retort

Abbreviations:

A – generator gas combustion chamber; B – distribution chamber of hot gas combustion products (gas heat carrier); C – oil shale retorting chamber; D – semi-coke cooling chamber; E – semi-coke unloading device; G – collector chamber; F – oil shale loading device; H – oil separation system.

Main material flows:

1 – oil shale; 2 – oil vapours and gas; 3 – semi-coke to the oil shale waste dump; 4 – generator gas; 5 – generator gas into the retort; 6 – generator gas for burning in the retort; 7 – generator gas into the cooling chamber; 8 – generator gas for firing in the power plant boilers; 9 – shale oil to the fuel storage of oil plant; 10 – fusses; 11 – air.

1.3.3.2 Solid heat carrier technology for oil shale processing

For the oil shale retorting process with a solid heat carrier, the oil shale with a particle size of 0–25 mm (as received) is used. The average output of the unit is 140 tons per hour and oil yield is about 13% [25].

A simplified layout of the solid heat carrier retorting process is presented in Figure 1.6. Since the SHC technology is more complicated the layout of the process is given with more details.

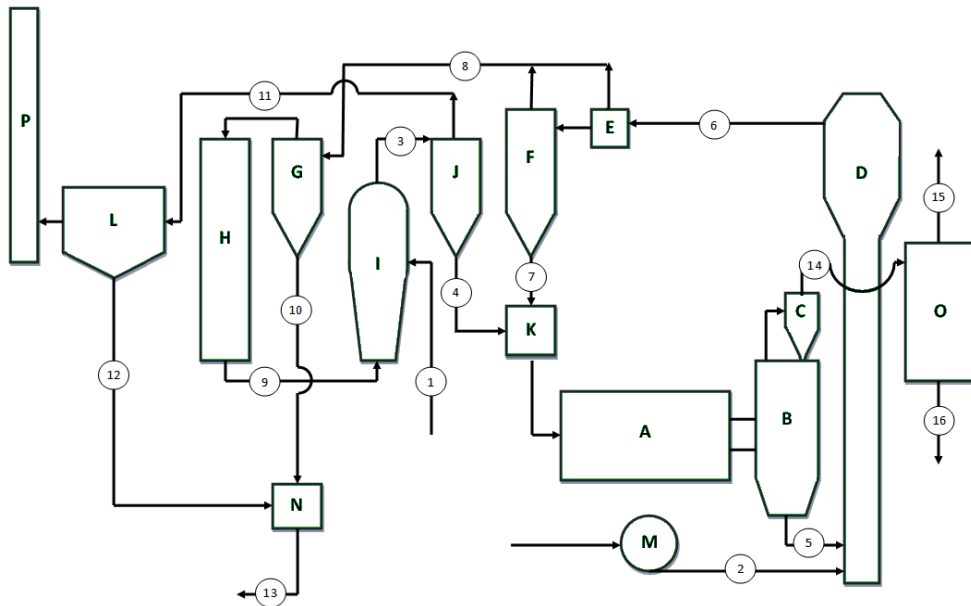


Figure 1.6. Principal layout of retorting process with a solid heat carrier

Abbreviations:

A – reactor for the oil shale pyrolysis; B – dust removal chamber; C – gas and oil vapours separator; D – aerofountain combustor (AFC); E – by-pass; F – hot ash (heat carrier) separation cyclone; G – ash separation cyclones (1st, 2nd and 3rd stage); H – waste heat (utilisation) boiler; I – aerofountain dryer (AFD); J – dried oil shale separation cyclones (the 1st, 2nd and 3rd stage); K – dried oil shale and hot ash (heat carrier) mixer; L – electrostatic separator; M – centrifugal air blower; N – pulp tank; O – oil condensation system; P – stack.

Main material flows:

1 – raw oil shale, 2 – compressed air; 3 – dried oil shale with flue gas; 4 – dried oil shale; 5 – semi-coke; 6 – hot ash (solid heat carrier) with gases after the combustion of semi-coke in AFC; 7 – hot ash (heat carrier); 8 – mixture of ash and AFC gases; 9 – flue gas; 10 – ash; 11 – flue gas to the electric precipitator; 12 – electric precipitator ash; 13 – ash pulp of the retort to the dredger unit of the power plant; 14 – oil vapours after cleaning; 15 – semi-coke gas delivered to power plant boilers; 16 – shale oil to the fuel storage of the oil plant.

Oil shale is heated up and dried with hot flue gas (600 °C) from the combustion of semi-coke in the aerofountain dryer (I). The dry oil shale is mixed with hot ash (750–800 °C) – a solid heat carrier. The ash is a by-product of semi-coke combustion in the aerofountain furnace (D). The ratio of heat carrier to oil shale is regulated by the required temperature of oil vapours leaving the retort, and controlled by the position of valve arranged in the heat carrier by-pass (E). The dried oil shale and hot ash (heat carrier) are mixed. The mixture of oil shale and

heat carrier is fed into the horizontal rotating retort (A). Thermal treatment of oil shale starts in the mixer (K) and continues in the retort. The contact of oil shale with heat carrier results in the intensive formation of shale oil vapours and semi-coke. The fine semi-coke particles are removed from the gas and oil vapours in the dust removal chamber (B) and separator (C). After the shale oil being condensed from oil vapours in the oil condensation system (O), the remaining semi-coke gas is directed into the power plant boilers for heat and power production. The semi-coke leaving the retort at 460 °C is delivered to the AFC (D) for the combustion. The gases from the AFC contain combustible compounds and surplus of sensible heat in the gases makes it possible to carry out the afterburning of these gases in the waste heat boiler H. The flue gas from the aerofountain dryer (I) is cleaned in the electric precipitator (L) and discharged into the atmosphere through the oil plant stack (P).

Various combustible co-products of shale oil production are used for heat generation required in oil shale processing in the described retorts. In order to obtain a gaseous heat carrier some of the generator gas is burned in the combustion chamber during oil shale retorting in the vertical retort.

The combustion products of generator gas are not emitted directly from the oil plant into the atmosphere, but are left in the generator gas as its components. Most of the generator gas is delivered to the power plant where it is burned in the boilers for heat and power generation. The yield of semi-coke in vertical retorts is approximately 49% [23]. The major share of waste from oil shale processing in gas generators is a solid residue – semi-coke. Today, the semi-coke, which contains about 10–13% of carbon, is not utilized, but stored in the dumps. In the future, it is planned to use semi-coke as a raw material in the cement industry.

The hot semi-coke ash is used for heating oil shale in the solid heat carrier retort. The hot semi-coke combustion product – flue gas is used for drying raw oil shale and after cleaning it is discharged into the atmosphere through the oil plant stack. The semi-coke gas is completely burned in the boilers of power plant and its combustion products are emitted into the atmosphere through the power plant stacks together with the flue gas of other fuels [24].

The advantages and disadvantages of SHC and GHC technologies are presented in Table 1.2.

Table 1.2 Advantages and disadvantages of SHC and GHC technology

Gas heat carrier technology	Solid heat carrier technology
<i>Advantages</i>	
Design simplicity and reliability.	The utilization of raw material (oil shale) is more efficient.
The industrial oil yield (16.5–17.5%) of GHC technology is higher than that of SHC technology (13%).	Allows the use of unenriched fine fraction of oil shale.
Major part of oil shale sulphur and all the carbonate CO ₂ goes to the dump with semi-coke.	Fairly low environmental pollution rate.
	The organic matter of oil shale is almost entirely utilized in the process, only 1–2% of carbon is stored with ash.
	There is no need for additional energy sources.
<i>Disadvantages</i>	
Only enriched oil shale with a larger particle size (25 – 125 mm) can be used, but mining gives approximately 30% fine oil shale.	A relatively complex design reduces its reliability and requires the synchronized work of all process elements.
The quantity of heat is directly related to the size of shale lump. The bigger the lump, the more time it takes to warm up and thus it reduces the output.	CO ₂ emission into the atmosphere, resulting from the combustion of semi-coke in the aerofountain combustor.
Direct combustion of gas to heat up the gas heat carrier results in a large quantity of low heating value gas.	
During the process the solid residues (semi-coke) hazardous to the environment are formed due to the high concentration of not completely distilled organic matter.	

2. CARBON BALANCE METHOD FOR ESTIMATING CO₂ EMISSIONS FROM THE OIL PRODUCTION PROCESS

2.1 General

Thermal processing of oil shale for the production of shale oil – pyrolysis – is a complex technological process during which the cleavage of the organic content of oil shale to shale oil, gas, and solid waste takes place. During the pyrolysis process the water separation occurs and carbon contained oil shale is distributed as shown in Figure 2.1.

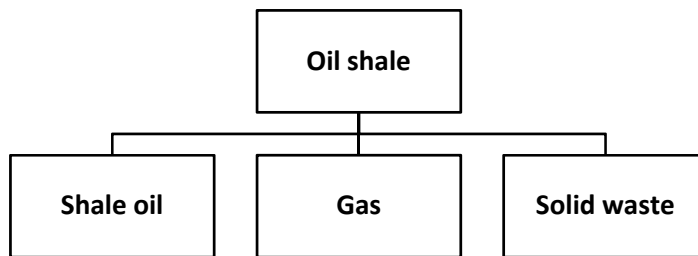


Figure 2.1 Principal distribution of oil shale organic carbon during thermal processing of oil shale

In order to calculate the emission amounts of carbon dioxide evolved during thermal processing of oil shale, the carbon emission factors should be found for the oil shale (carbon input) and shale oil, gas, and semi-coke (all outputs). The reason why to consider the carbon balance instead of the CO₂ balance is the fact that CO₂ balance makes the input-output analysis of carbon more complicated as it includes also the carbon oxidation factor. The use of carbon balance method increases the transparency of the analysis.

For this purpose, it is important to define the system boundaries, which lead to the most appropriate estimation of specific products' emission, at the same time minimising the amount of data needed.

The general principle is to design a set of formulas satisfying the condition: „everything that goes in also goes out“, or in other words, the amount of carbon entering the system boundaries must be equal to the amount of carbon leaving these boundaries:

$$\sum C_{input} = \sum C_{product} + C_{emissions} \quad (2.1)$$

$$CO_2 \text{ emissions} = \sum_i CO_{2i} = \sum_i AD_i \times NCV_i \times q_i, \quad (2.2)$$

where AD_i is activity data (fuel consumption in tons or Nm^3) for the fuel i , NCV_i is the net heating value (TJ/t or TJ/ Nm^3) and q_i is the carbon emission factor of fuel i (tC/TJ). For converting the carbon content to CO_2 emissions or vice versa the following formula is used:

$$CO_2 \text{ emissions} = \frac{M(CO_2)}{M(C)} \times C = 3.664 C, \quad (2.3)$$

where C is the carbon content (tons), $M(CO_2)$ is the molar mass of CO_2 and $M(C)$ is the molar mass of carbon [27].⁴

2.2 System boundaries

It is important to define the production unit system boundaries, which lead to the most appropriate accounting of emissions, at the same time minimising the amount of data needed to estimate the carbon content of specific products.

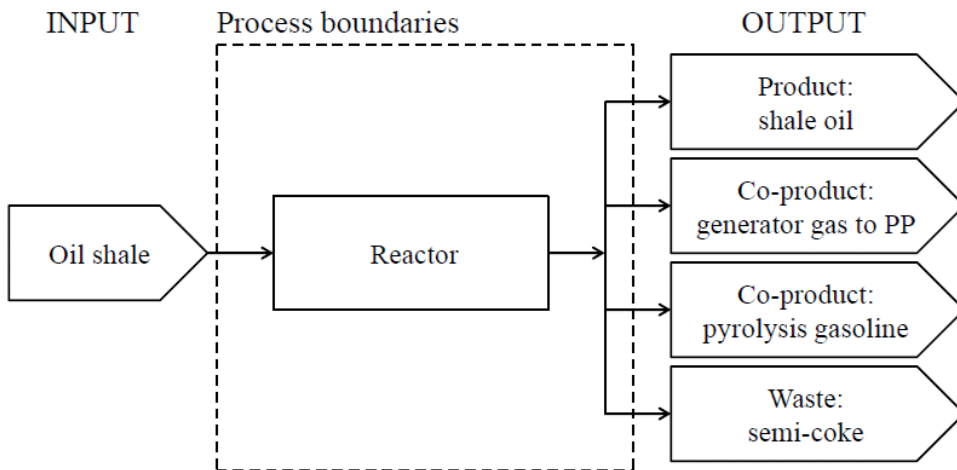


Figure 2.2 Process boundaries for a gaseous heat carrier unit

⁴ The result of the formula (2.3), 3.664 C is obtained by dividing 44.009/12.011.

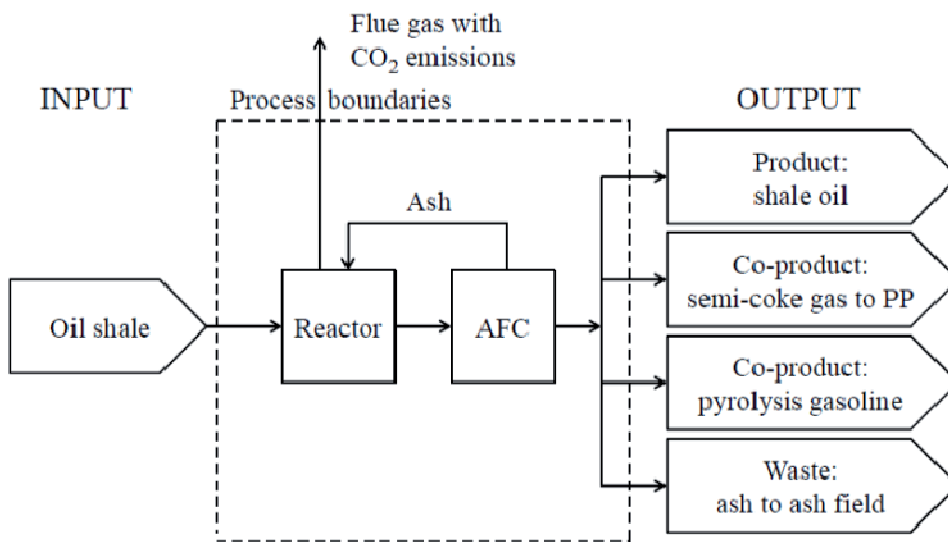


Figure 2.3 Process boundaries for a solid heat carrier unit

In Figure 2.2 and Figure 2.3 the process boundaries for gaseous and solid heat carrier technologies are presented.

In both cases all carbon entering the system (installation) is derived from oil shale. The amount of carbon can be calculated using the formula (2.4). This requires, however, developing the technology-specific carbon emission factor for oil shale.

The output products and residues from the process are the following: raw shale oil, generator or semi-coke gas, ash or semi-coke, depending on the technology used. In the case of SHC technology also flue gas is emitted, in which the carbon as CO₂ escapes into the atmosphere. The generator gas and semi-coke gas are the process residues, but at the same time also valuable fuels for power plants. In order to calculate the amount of carbon, which leaves the process with semi-coke gas or generator gas it is required to find the technology-specific carbon emission factors for these gases.

2.3 Amount of carbon entering the process with oil shale

Amount of carbon (C_{os}) that enters the pyrolysis process with the feedstock oil shale can be calculated by the following formula:

$$C_{os} = q_{c os} \times B'_{os} \quad (2.4)$$

2.3.1 Method for estimating the carbon emission factor of oil shale

2.3.1.1 Oil shale carbon emission factor for the solid heat carrier technology

In order to calculate the amount of carbon in oil shale C_{os} (t) with the formula (2.4), where only the quantity of feedstock oil shale B_{os}^r (t) and the annual average lower heating value of oil shale as received Q_{os}^r (MJ/t) are known, it is at first necessary to find the oil shale carbon emission factor (CEF) which can be calculated by the formula [28]:

$$q_{c os} = 10 \times \frac{C^r + (44/12) \times k_{CO_2} \times (CO_2)_M^r}{Q_{os}^{r'}}, \quad (2.5)$$

where

$q_{c os}$ – carbon emission factor of oil shale, tC/TJ;

C^r – amount of carbon in oil shale as received, %;

$Q_{os}^{r'}$ – corrected heating value of oil shale as received, MJ/t;

$(CO_2)_M^r$ – mineral carbon dioxide content of oil shale as received, %;

k_{CO_2} – decomposition rate of the carbonate part of semi-coke in the aerofountain combustor.

In the solid heat carrier unit oil shale semi-coke moves from the reactor to the aerofountain combustor for afterburning where a certain decomposition of semi-coke mineral matter occurs (see Figure 1.6). The combustion of semi-coke in the aerofountain furnace takes place under the conditions of air shortage ($\alpha < 1$). The decomposition rate of semi-coke k_{CO_2} can be calculated as follows [29]:

$$k_{CO_2} = 1 - \frac{(CO_2)_{ash}^d / A_{ash}^d}{(CO_2)_M^d / A_{os}^d}, \quad (2.6)$$

where

$(CO_2)_{ash}^d$ – mineral carbon dioxide content of dry heat carrier from AFC, %;

$(CO_2)_M^d$ – mineral carbon dioxide content of dry oil shale, %;

A_{ash}^d – content of ash in the solid heat carrier, %;

A_{os}^d – content of ash in dry oil shale, %.

In this work, the value of k_{CO_2} used in carbon balance calculations is taken equal to 0.256. The value is based on the test results in Narva Oil Plant performed by the Oil Shale Research Institute of Tallinn University of Technology in 2003 [30].

Because of the smaller extent of carbonate decomposition, the corrected lower heating value of oil shale $Q_{os}^{r'}$ (MJ/kg) can be calculated [4]:

$$Q_{os}^{r'} = Q_{os}^r + \Delta Q_c, \quad (2.7)$$

where

Q_{os}^r – lower heating value of oil shale as received, MJ/kg;

ΔQ_c – heat effect due to incomplete decomposition of carbonate minerals, MJ/kg.

Heat is released mainly during the combustion of organic matter, but the thermal effects occurring in the fuel mineral matter cannot be ignored. During the oil shale combustion process, the thermal effects related to the decomposition of carbonate minerals can be considered the most important ones [16].

The thermal effect due to incomplete decomposition of carbonates can be calculated by A. Ots [16] as follows:

$$\Delta Q_c = 0.0406 (1 - k_{CO_2}) \times (CO_2)_M^r, \quad (2.8)$$

where the coefficient 0.0406 is taken from the [26].

To convert the quantity of oil shale given in natural units (tons) to energy units we can use a simple formula:

$$B'_{os} = B_{os} \times Q_{os}^r, \quad (2.9)$$

where

B'_{os} – oil shale consumption, TJ;

B_{os} – oil shale consumption, kt;

Q_{os}^r – lower heating value of oil shale as received, MJ/kg.

In order to find the content of mineral carbon dioxide $(CO_2)_M^d$ in oil shale as received, a well-known conversion formula can be used [31]:

$$(CO_2)_M^r = (CO_2)_M^d \times (100 - W^r)/100, \quad (2.10)$$

where

$(CO_2)_M^d$ – content of mineral CO_2 in oil shale dry matter, %;

W^r – moisture content of oil shale as received, %.

Based on the research by H. Arro, A. Prikk and T. Pihu [13], the following formulas were developed for determining the mineral CO_2 , ash content and moisture content of oil shale:

$$(CO_2)_M^d = -0.112 (Q_{os}^d)^2 + 1.0723 Q_{os}^d + 20.323, \quad (2.11)$$

$$A^d = 0.052 (Q_{os}^d)^2 - 2.3049 Q_{os}^d + 68.929, \quad (2.12)$$

$$W^r = 0.6695 Q_{os}^r + 5.9141 \quad (2.13)$$

Applying the conversion formulas [31], heating value of the oil shale as received can be converted to heating value of dry matter in oil shale

$$Q_{os}^d = (Q_{os}^r + 0.02442 W^r) \times 100 / (100 - W^r), \quad (2.14)$$

where

Q_{os}^r – lower heating value of oil shale as received, MJ/kg;

W^r – moisture content of oil shale as received, %.

Ash content in oil shale as received A^r (%) can be found through converting formula (2.12) to the following form:

$$A^r = A^d \times (100 - W^r) / 100. \quad (2.15)$$

The carbon content in dry matter of oil shale C^d can be found based on ultimate analysis of oil shale (see Table 1.1) [16]:

$$C^d = 0.7745 R^d, \quad (2.16)$$

where

R^d – organic part in dry matter of oil shale, %.

The organic part in dry matter of oil shale [13]:

$$R^d = (100 \times Q_{os}^d + 3.882 + (CO_2)_M^d - 13.297 S_p^d) / 34.56, \quad (2.17)$$

where

S_p^d – content of pyritic sulphur, %.

The content of pyritic (marcasite) sulphur S_p^d can be found applying the following formula [13]:

$$S_p^d = 0.534 FeS_2^d, \quad (2.18)$$

where

FeS_2^d – content of pyrites in dry oil shale [13], %.

$$FeS_2^d = FeS_2 \times T^d / 100, \quad (2.19)$$

where

FeS_2 – content in the oil shale sandy-clay part (is taken equal to 9.3%, see Table 1.1).

The carbon content of oil shale as received C^r can be found using the following conversion formula [31]:

$$C^r = C^d \times (100 - W^r)/100. \quad (2.20)$$

The content of apparent combustible matter P^r can be calculated by the following formula [16]:

$$P^r = 100 - A^r - (CO_2)_M^r - W^r, \quad (2.21)$$

and sandy-clay part in dry oil shale T^d (%) by the next formula [16]:

$$T^d = A^d - 1.217 (CO_2)_M^d. \quad (2.22)$$

2.3.1.2 Carbon emission factor of oil shale for the gaseous heat carrier technology

During the oil shale retorting process in gas generators with gaseous heat carrier the retorting residue semi-coke is not burnt, but disposed in a waste dump. Therefore, for the calculation of carbon amount entering the process (formula 2.4), the carbon emission factor of oil shale q_{cos} (tC/TJ) has to be calculated using a simplified formula:

$$q_{cos} = 10 \times C^r / Q_{os}^r, \quad (2.23)$$

where

C^r – carbon content of oil shale as received, %;

Q_{os}^r – heating value of oil shale as received, MJ/kg.

The carbon content of oil shale as received C^r can be calculated by the same methodology as in Chapter 2.3.1.

2.4 Amount of carbon leaving the process with gas

Amount of carbon leaving the pyrolysis process with semi-coke gas C_{scg} (t) or generator gas C_{gg} (t) can be calculated by the following formulas:

$$C_{scg} = q_{scg} \times B_{scg}, \quad (2.24)$$

where

q_{scg} – carbon emission factor of semi-coke gas, tC/TJ;

B_{scg} – amount of semi-coke gas, TJ.

$$C_{gg} = q_{gg} \times B_{gg}, \quad (2.25)$$

where

q_{gg} – carbon emission factor of generator gas, tC/TJ;

B_{gg} – amount of generator gas, TJ.

In the chapters 2.4.1 and 2.4.2 a method for estimating the carbon emission factors for semi-coke and generator gas is described.

2.4.1 Method for estimating the carbon emission factors for semi-coke and generator gas

The approach for estimating the carbon emission factors of oil shale semi-coke and generator gas is based on the actual composition of gas. The gas composition, breaking the gas into methane, ethane, propane, other hydrocarbons and other gases determines also the heating value and its carbon content.

2.4.1.1 Carbon emission factor for SHC semi-coke gas

The semi-coke gas formed in the SHC unit is characterised by a high content of burning compounds and has approximate lower heating value of 39.8–46.8 MJ/kg [33]. Besides methane, ethane and ethene are also the main compounds of semi-coke gas. The composition of semi-coke gas by compounds varies somewhat in different sources, since the compounds of gas depend on the thermal processing regime. At the same time those differences are not significant.

The carbon emission factor of SHC semi-coke gas can be calculated by the following formula [23]:

$$q_{c\ scg} = 10 \times (12/16CH_4 + 24/30 C_2H_6 + 24/28 C_2H_4 + 36/44 C_3H_8 + 36/42 C_3H_6 + 48/58 C_4H_{10} + 48/56 C_4H_8 + 60/72 C_5H_{12} + 60/78 C_5H_{10} + 72/82 C_6H_{10} + 12/44 CO_2 + 12/28 CO) / Q'_{scg}, \quad (2.26)$$

or

$$q_{c\ scg} = 10 \times \sum C / Q'_{scg}, \quad (2.27)$$

where

$q_{c\ scg}$ – carbon emission factor of semi-coke gas, tC/TJ;

$\sum C$ – total carbon content in semi-coke gas (in weight units), %;

Q'_{scg} – heating value of semi-coke gas, MJ/kg;

Q^r_{scg} – heating value of semi-coke gas, MJ/Nm³.

The heating value of semi-coke gas (MJ/kg) can be found by dividing the lower heating value in (MJ/Nm³) with the density of semi-coke gas:

$$Q_{scg}^{r'} = Q_{scg}^r / \rho_{scg}, \quad (2.28)$$

where

ρ_{scg} – density of semi-coke gas, kg/Nm³.

2.4.1.2 Carbon emission factor of generator gas

In the vertical retorts (gas generators) with cross-flow of heat carrier due to direct burning of gas for heating up the heat carrier, the large volumes of gas with a very low heating value are formed.

For calculating the carbon emission factor of generator gas $q_{c\,gg}$ (tC/TJ) the following formula can be used:

$$q_{c\,gg} = 10 \times \Sigma C / Q_{gg}^{r'}, \quad (2.29)$$

where

$Q_{gg}^{r'}$ – lower heating value of generator gas, MJ/kg;

ΣC – total carbon content in generator gas (in weight units), %.

2.5 Amount of carbon leaving the process with shale oil

Amount of carbon stored in shale oil C_{so} (t) can be calculated as:

$$C_{so} = q_{c\,so} \times B'_{so}, \quad (2.30)$$

where

$q_{c\,so}$ – carbon emission factor of shale oil, tC/TJ (is taken from [33]);

B'_{so} – amount of produced shale oil, TJ.

2.6 Amount of carbon leaving the process with pyrolysis gasoline

The semi-coke and generator gas contain also pyrolysis gasoline. According to the plant data, the content of pyrolysis gas in semi-coke gas is approximately 200 g/Nm³ and in generator gas 15 g/Nm³. In the current work the amounts of pyrolysis gasoline have not been measured, but calculated.

$$C_{pg} = q_{c\,pg} \times B'_{pg}, \quad (2.31)$$

where

$q_{c\,pg}$ – carbon emission factor of pyrolysis gasoline, tC/TJ;

B'_{pg} – production of pyrolysis gasoline, TJ.

The country specific carbon emission factor of gasoline q_{cpg} is published in the Estonian National GHG Report to UNFCCC [3].

2.7 Amount of carbon stored with ash

After semi-coke combustion in the aerofountain combustor of the SHC device, a solid waste – ash is formed. The ash amount $B_{ash}(t)$ removed from the SHC process can be calculated as follows:

$$B_{ash} = A_{ash}^r \times B_{os}, \quad (2.32)$$

where

A_{ash}^r – ash content in solid heat carrier material, %.

$$A_{ash}^r = (A_{os}^r + ((CO_2)_M^r \times (1 - k_{CO_2})) + m_s)/100, \quad (2.33)$$

where

m_s – increase of ash amount because of sulphur binding.

The carbon content of ash removed from a SHC unit is less than one percent by ash weight [4] and can be calculated as:

$$C_{ash} = (B_{ash}/0.99) - B_{ash}. \quad (2.34)$$

As the result of oil shale thermal processing in a gaseous heat carrier units a solid residue of used oil shale – semi-coke is formed, which accounts for about 58% [17] of the amount of used oil shale. Similar to oil shale, semi-coke consists of organic and mineral matter. The content of oil shale organic matter used in generators is about 35%. The content of organic matter in semi-coke is (mainly in the form of carbon) about 10–13% [17].

The amount of carbon stored with semi-coke $C_{sc}(t)$ can be calculated as a difference between the carbon content of the source oil shale $C_{os}(t)$ and carbon stored with shale oil $C_{so}(t)$ generator gas $C_{gg}(t)$ and pyrolysis gasoline $C_{ppg}(t)$:

$$C_{sc} = C_{os} - C_{so} - C_{gg} - C_{ppg}. \quad (2.35)$$

Amount of solid waste of gaseous heat carrier – semi-coke $B_{sc}(t)$ can be calculated as follows:

$$B_{sc} = B_{os} \times (A^r + (CO_2)_M^r)/100 + C_{sc}. \quad (2.36)$$

2.8 Amount of carbon emitted with flue gas (SHC technology)

In the case of oil shale pyrolysis with a solid heat carrier unit the solid residue (semi-coke) will be afterburned in the aerofountain combustor. The flue gas from the AFC that contains combustible compounds enables afterburning of these gases in the waste heat boiler. After cleaning the gas will be discharged in the atmosphere through the oil plant stack.

The amount of carbon in flue gas C_{fg} (t) can be calculated as a difference between the carbon amount of oil shale and carbon stored in shale oil, semi-coke gas, pyrolysis gasoline and ash:

$$C_{fg} = C_{os} - C_{so} - C_{gg} - C_{ppg} - C_{ash}. \quad (2.37)$$

The amount of CO₂ emitted with the flue gas to the atmosphere $CO_{2\ fg}$ can be calculated as follows:

$$CO_{2\ fg} = \frac{44}{12} C_{fg} \quad (2.38)$$

The results of calculations for different oil plants and technologies are presented in Chapter 3.

3. RESULTS OF CARBON BALANCE CALCULATIONS FOR OIL SHALE PYROLYSIS IN 2010

3.1 Description of the calculation model

A calculation model has been developed based on the methodology described in Chapter 2. At the limited amount of activity data the model allows to calculate the quantity of carbon entering the process with feedstock oil shale and the quantity of carbon leaving the process with pyrolysis products, co-products and residues or directly emitted to the atmosphere during the process.

The activity data for a model, as oil shale consumption, oil and gas production and their heating values, are obtained from oil production companies. In this study the annual data have been used, but the model allows using also the activity data for a shorter period (a month, quarter).

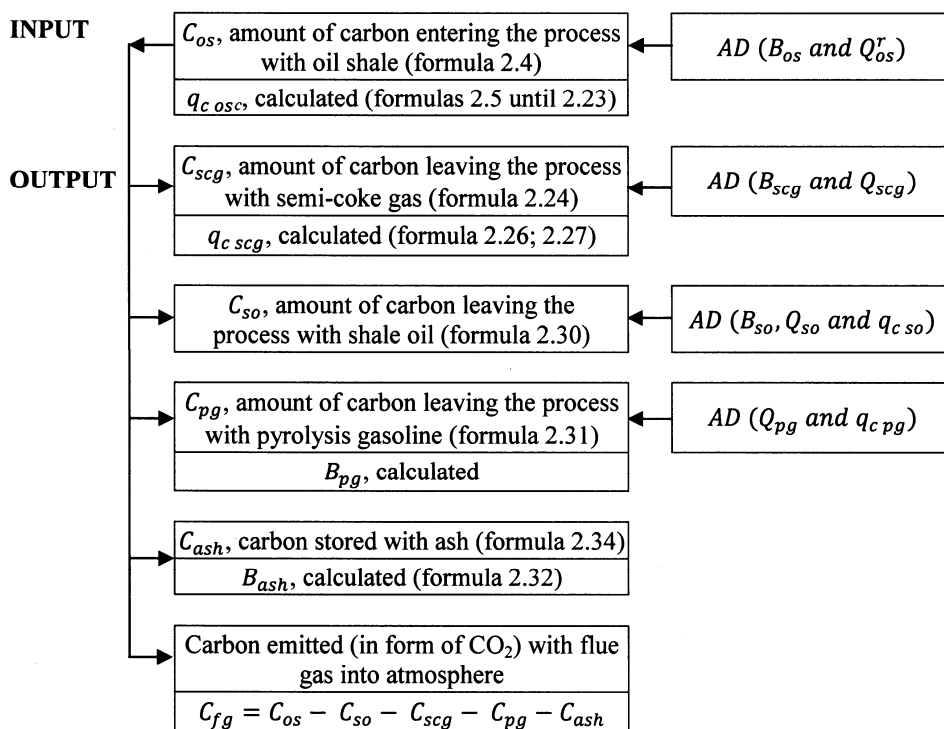


Figure 3.1 A simplified diagram of the SHC carbon balance calculation model

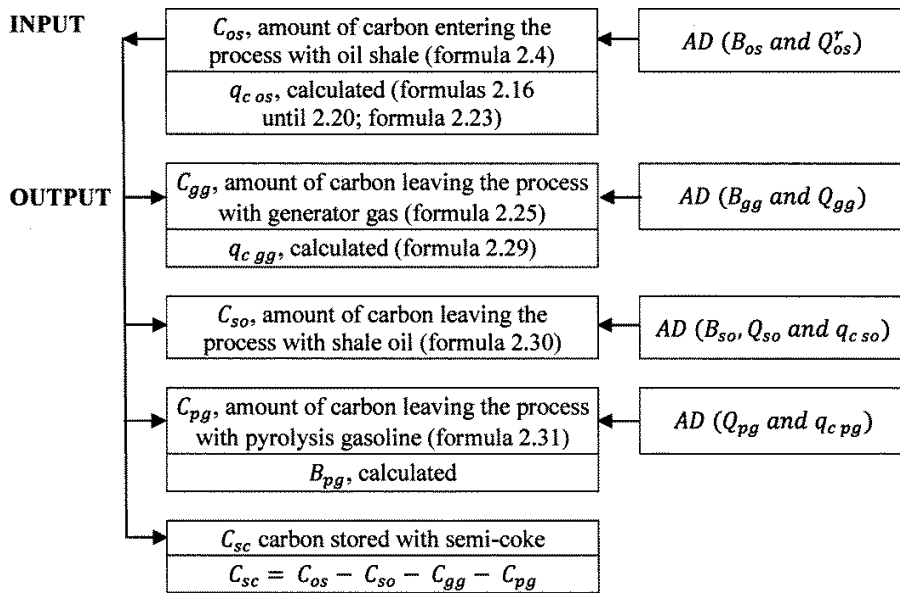


Figure 3.2 A simplified diagram of the GHC carbon balance calculation model

3.2 Calculation results of carbon balance mass flows participating in the oil shale pyrolysis process

3.2.1 Calculation results for the amounts of carbon entering the process with oil shale

With using the formulas 2.2 to 2.24 in Chapter 2, the amounts of carbon entering the pyrolysis process with oil shale by plant and technology can be calculated. The summary of the calculation results is given in Table 3.1. The data on oil shale consumption and average annual lower heating values have been collected from oil plants⁵. The calculations are based on the activity data (AD) of the year 2010.

Table 3.1 Amounts of carbon entering the pyrolysis process with oil shale by plant and technology in 2010

Indicator	Unit	SHC			GHC	
		Narva	VKG*	Kiviõli	VKG	Kiviõli
Oil shale consumption, B_{os}	kt	1747.36	263.36	22.48	1682.83	449.18
Lower heating value of oil shale as received, Q'_{os}	MJ/kg	8.43	8.43	9.76	12.57	9.12

⁵ The same data was used for preparation of Estonian National GHG inventory report 1990–2010 to the UNFCCC [2].

Carbon emission factor of oil shale, q_{os}	tC/TJ	23.29	23.31	23.18	22.93	23.24
Amount of carbon entering the pyrolysis process with oil shale, C_{os}	kt	343.27	51.75	5.08	485.11	95.20
Total carbon input	%	100	100	100	100	100

* The solid heat carrier unit (Petroter) of VKG Oil AS was in 2010 only in the experimental stage, and therefore the results may deviate from the data of later years

3.2.2 Calculation results for the carbon leaving the process with shale oil

Summary of the calculation results for the carbon leaving the process with raw shale oil by plant and technology is given in Table 3.2.

In Estonia, the country specific average carbon emission factor of shale oil is established by the regulation of the Ministry of Environment N° 94, December 8, 2006 [33].

Table 3.2 Amounts of carbon leaving the pyrolysis process with shale oil by plant and technology, 2010

Indicator	Unit	SHG			GHC	
		Narva	VKG	Kiviõli	VKG	Kiviõli
Shale oil production, B_{os}	kt	190.45	29.56	2.77	266.89	65.70
Average heating value of shale oil, Q_{so}	MJ/kg	39.51	37.36	40.08	40.00	39.50
Carbon emission factor of shale oil, q_{so}	tC/TJ	21.1	21.1	21.1	21.1	21.1
Amount of carbon leaving the process with shale oil, C_{so}	kt	158.75	23.31	2.34	225.26	54.76
Carbon leaving the process with shale oil	%	46.25	45.03	46.07	46.43	57.52

3.2.3 Estimation of carbon emission factor for semi-coke and generator gas

Using formulas 2.28 and 2.30 and average annual composition of semi-coke gas and generator gas obtained from oil plants, the carbon emission factors of semi-coke gas and generator gas were calculated. The calculation results are presented in Table 3.3.

Table 3.3 Carbon emission factors of semi-coke gas and generator gas from oil shale thermal processing by oil production factory, 2010

Co-product	Carbon emission factor, tC/TJ			
	Narva Oil Plant (Enefit-140)	VKG Oil Plant (Petroter)	Kiviõli Oil Plant (SHC-500)	Average
Semi-coke gas	18.78	18.83	17.97	18.77
Generator gas	–	50.36	51.17	50.52

The value of carbon emission factor of retort gas (semi-coke gas or generator gas) depends on the technology used. However, even for the same technology minor differences between the carbon emission factors of different oil plants can be observed since each oil producer has introduced his own modifications in the technology.

The annual average values of gas composition are calculated on the basis of quarterly data collected from oil plants. In 2010, the values of carbon emission factors of semi-coke gas remained in the range of 17.97–18.83 tC/TJ, the weighted average being 18.77 tC/TJ. Carbon emission factors of generator gas were in the range of 50.36–51.17 tC/TJ, and the weighted average value was 50.52 tC/TJ. The value of carbon emission factor is calculated by the gas composition, which depends on the operation mode of the unit. Therefore, the values of carbon emission factors should be calculated annually.

3.2.4 Calculation results of the carbon amount leaving the process with semi-coke gas or generator gas

Summary of calculation results on the carbon leaving the process with semi-coke or generator gas by plant and technology is presented in Table 3.4. and Table 3.5.

Table 3.4 Amounts of carbon leaving the pyrolysis process with semi-coke or generator gas by plant and technology, 2010

Indicator	Unit	SHC			GHC	
		Narva	VKG	Kiviõli	VKG	Kiviõli
Semi-coke gas / generator gas production, B_{scg}/B_{gg}	MNm ³	59.82	9.93	1.11	857.82	204.44
Heating value of semi-coke gas / generator gas, Q_{scg}/Q_{gg}	MJ/Nm ³	47.37	40.47	28.65	3.19	2.10
Carbon emission factor of semi-coke gas / generator gas, $q_{c\ scg}/q_{c\ gg}$	tC/TJ	18.78	18.83	17.97	50.36	51.17
Amount of carbon leaving the process with semi-coke gas / generator gas, C_{scg}/C_{gg}	kt	53.22	7.57	0.57	137.81	21.97
Carbon leaving the process with gas	%	15.50	14.64	11.26	28.41	23.08

3.2.5 Calculation results of the carbon amount leaving the process with pyrolysis gasoline

At first, the amount of pyrolysis gasoline was calculated. According to the oil plants data, 200 grams of pyrolysis gasoline is derived per one normal cubic metre of semi-coke gas and 15 grams of pyrolysis gasoline per that of generator gas.

The main part of the pyrolysis gasoline is used for liquefying heavy fraction of oil in the oil preparation unit. Summary of calculation results of carbon leaving the process with pyrolysis gasoline is given by plant and technology in Table 3.5.

Table 3.5 Amounts of carbon leaving the process with pyrolysis gasoline by plant and technology, 2010

Indicator	Unit	SHC			GHC	
		Narva	VKG	Kiviõli	VKG	Kiviõli
Amount of pyrolysis gasoline, B_{pg}	kt	10.48	1.99	0.22	12.87	3.07
Heating value of pyrolysis gasoline, Q_{pg}	MJ/kg	44.00	44.00	44.00	44.00	44.00
Carbon emission factor of gasoline, q_{pg}	tC/TJ	19.90	19.90	19.90	19.90	19.90
Amount of carbon leaving the process with pyrolysis gasoline, C_{pg}	kt	10.48	1.74	0.19	11.27	2.69
Carbon leaving the process with pyrolysis gasoline	%	3.05	3.36	3.83	2.32	2.82

3.2.6 Calculation results of the carbon amount leaving the process with solid waste

In Table 3.6 the calculation results of the carbon amount leaving the pyrolysis process with solid waste are presented. The solid waste of the solid heat carrier unit is ash, the semi-coke combustion residue. The solid waste of oil shale thermal processing in gas generators is semi-coke.

Table 3.6 Amounts of carbon leaving the pyrolysis process with solid waste by plant and technology, 2010

Indicator	Unit	SHC			GHC	
		Narva	VKG	Kiviõli	VKG	Kiviõli
Solid waste production, B_{sc}/B_{ash}	kt	1054.76	158.96	12.68	932.79	289.24
Amount of carbon in solid waste, C_{sc}/C_{ash}	kt	10.33	1.56	0.12	110.78	15.79
Carbon leaving the process with solid waste	%	3.01	3.01	2.45	22.84	16.58

3.2.7 Calculation results of the carbon amount leaving the process with flue gas

In Table 3.7 the calculation results of the carbon amount leaving the pyrolysis process with flue gas are presented. Carbon in flue gas is emitted to the atmosphere in the form of carbon dioxide.

Table 3.7 Amounts of carbon leaving the pyrolysis process with flue gas by plant and technology, 2010

Indicator	Unit	Plant		
		Narva	VKG	Kiviõli
Amount of carbon leaving the process with flue gas, B_{fg}	kt	99.05	15.85	1.72
Carbon dioxide emitted with flue gas	tCO ₂	405.15	64.45	6.78
Carbon leaving the process with flue gas	%	32.19	33.97	36.40

In Table 3.8 the carbon balance of oil shale pyrolysis is presented. The amount of carbon entering the pyrolysis process with oil shale is taken equal to 100% while the amounts of carbon leaving the process with products, co-products, solid waste and gaseous waste are presented in natural units (t) and in percents. All activity data and calculation results are presented by oil plant and by technology used.

Table 3.8 Carbon balance of oil shale pyrolysis, 2010

	SHC						GHC			
	Narva		VKG		Kiviõli		VKG		Kiviõli	
	kt	%	kt	%	kt	%	kt	%	kt	%
Oil shale	343.27	100.00	51.75	100.00	5.08	100.00	485.11	100.00	95.20	100.00
Shale oil	158.75	46.25	23.31	45.03	2.34	46.07	225.26	46.43	54.76	57.52
Semi-coke gas	53.22	15.50	7.57	14.63	0.57	11.26	–	–	–	–
Generator gas	–	–	–	–	–	–	137.81	28.41	21.97	23.08
Pyrolysis gasoline	10.48	3.05	1.74	3.36	0.19	3.83	11.27	2.32	2.69	2.82
Solid waste	10.33	3.01	1.56	3.01	0.12	2.45	110.78	22.84	15.79	16.58
Flue gas	110.50	32.19	17.58	33.97	1.85	36.40	–	–	–	–

For better visualization of the results the data given in Table 3.8 are also depicted graphically in Figure 3.3 and Figure 3.4.

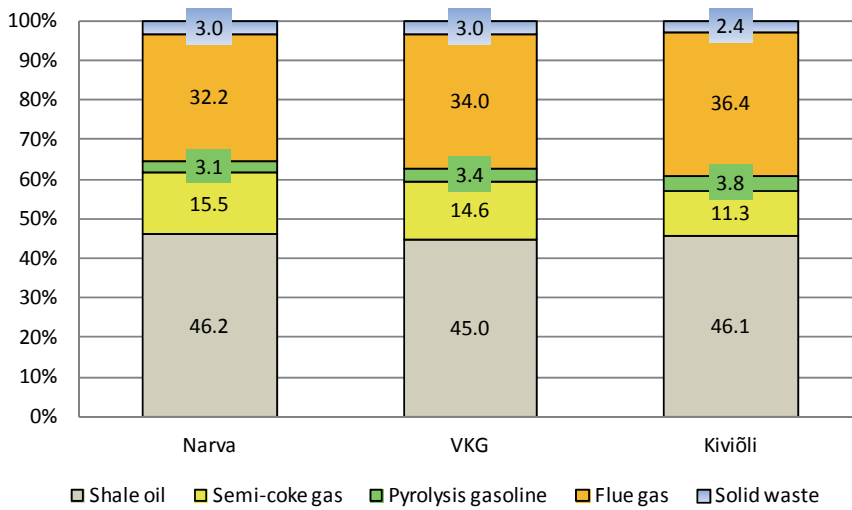


Figure 3.3 Carbon distribution between pyrolysis products and waste by plants using the solid heat carrier technology in 2010

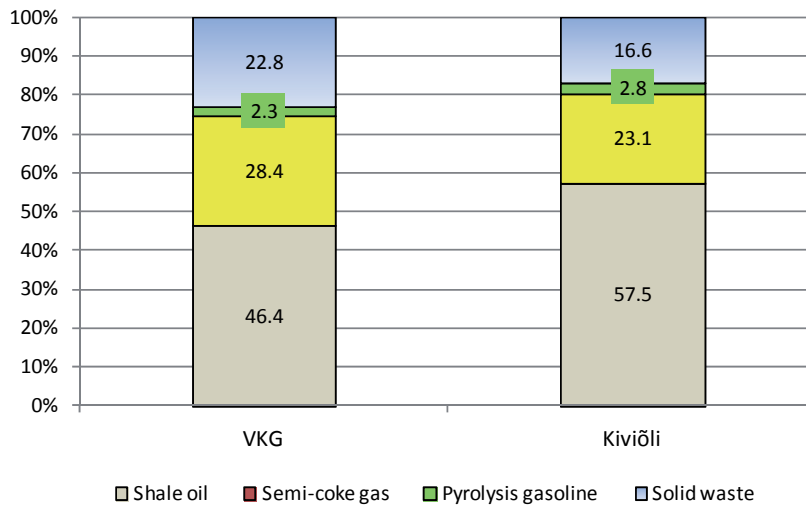


Figure 3.4 Carbon distribution between pyrolysis products and waste by plants using the gaseous heat carrier technology in 2010

As it follows from the data presented in Table 3.8, Figure 3.3 and Figure 3.4, carbon entering the thermal treatment process of the solid heat carrier technology with oil shale as a feedstock material leaves the process as follows:

- 45.0–46.2% with shale oil,

- 11.3–15.5% with semi-coke gas (which is used as a fuel for electricity and heat production in power plants nearby),
- 3.1–3.8% with pyrolysis gasoline,
- 2.4–3.0% with semi-coke and
- 32.2–36.4% with flue gas to the atmosphere in the form of CO₂.

At thermal processing of oil shale in gas generators the carbon entering the process with oil shale is distributed by products leaving the process as follows:

- 46.4–57.5% with shale oil,
- 23.1–28.4% with generator gas,
- 2.3–2.8% with pyrolysis gasoline and
- 16.6–22.8% with semi-coke to landfill.

3.3 Specific carbon dioxide emission factor of produced oil

In addition to the amount of carbon emitted with flue gas to the atmosphere, a second important factor – carbon dioxide emission per unit of produced oil ($q_{CO_2/t}$) can be calculated for the SHC technology. To this end, the amount of carbon dioxide in flue gas is found and the result is divided by the quantity of oil produced from oil shale.

$$q_{CO_2/t} = CO_{2\ fg} / B_{so}, \quad (3.1)$$

where

$q_{CO_2/t}$ – specific carbon dioxide emission factor per unit of oil produced, tCO₂/t oil;

$CO_{2\ fg}$ – estimated emissions of carbon dioxide, kt;

B_{so} – oil shale consumption for oil production, TJ.

The amount of carbon dioxide leaving the pyrolysis process with flue gas can be estimated using the following formula:

$$CO_{2\ fg} = \frac{44}{12} C_{fg}, \quad (3.2)$$

where

C_{fg} – amount of carbon leaving the process with flue gas, kt.

The gaseous heat carrier technology is a closed process, and no carbon dioxide emission to the atmosphere can be observed.

In Table 3.9 the values of specific emission factor for CO₂ by oil plant and weighted average of the specific emission expressed in tons of CO₂ per ton of oil are presented.

Table 3.9 Specific carbon dioxide emission factor per unit of produced oil by plant in 2010, tCO₂/t oil

Indicator	Plant		
	Narva	VKG	Kiviõli
Shale oil production, kt	190.45	29.56	2.77
Amount of carbon in flue gas, kt	110.50	17.58	1.85
Amount of CO ₂ , kt	405.15	64.45	6.78
Specific emission factor, tCO ₂ /t oil	2.13	2.18	2.45
Average specific emission factor, tCO ₂ /t oil	2.14		

The value of specific carbon dioxide emission factors ($q_{CO_2/t}$) of solid heat carrier technology is the lowest in Narva and the highest in Kiviõli Oil Plant ranging between 2.13–2.45 tons of carbon dioxide per ton of oil produced. In 2010, the weighted average value of specific CO₂ emission factor for solid heat carrier technology was 2.14 tCO₂/t oil.

3.4 Oil yield

The key indicator of the quality of oil shale as a raw material for thermal processing is the laboratory oil yield. The oil yield from oil shale is in direct correlation with the heating value of dry oil shale.

The correlation between the heating value of dry oil shale and oil yield can be expressed by the formula compiled by V. Kattai on the basis of 600 oil shale analyses [17]:

$$T_L = 1.78 Q_{os}^d, \quad (3.3)$$

According to the data from oil plants, the oil shale with the average heating value of 8.43–12.57 MJ/kg (Table 3.1 and Table 3.10) was consumed in oil plants. The industrial oil yield has been calculated by dividing the produced quantity of oil (t) with the consumed amount of oil shale (t). The industrial oil yield for the solid heat carrier units remained in the range of 10.9–12.3% and that of gas generators 14.6–15.9% (Table 3.10).

Table 3.10 Oil yield of oil shale by plant and technology in 2010

Indicator	Unit	SHC			GHC	
		Narva	VKG	Kiviõli	VKG	Kiviõli
Moisture content of oil shale, W ^r	%	11.56	11.56	12.45	14.33	12.02
Average heating value of oil shale as received, Q _{os} ^r	MJ/kg	8.43	8.43	9.76	12.57	9.12
Industrial oil yield, T	%	10.9	11.2	12.3	15.9	14.6

Indicator	Unit	SHC			GHC	
		Narva	VKG	Kiviõli	VKG	Kiviõli
The weighted average industrial oil yield, $T_{average}$	%	11.0			15.6	
Average heating value of oil shale dry matter, Q_{os}^d	MJ/kg	9.86	9.86	11.50	15.08	10.70
Laboratory oil yield, T_L	%	17.5	17.6	19.8	26.8	19.1
Laboratory oil yield, weighted average, $T_{L, average}$	%	17.6			25.3	
Ratio of industrial oil yield to laboratory oil yield	%	62.1	64.0	60.2	59.1	76.8

In 2010, the weighted average industrial oil yield was about 11.0% for SHC technology and 15.6% for GHC technology. The weighted average of laboratory oil yield totalled 17.6% and 25.3%, respectively. Thus, the industrial oil yield of solid heat carrier plants was in the range of 62.1–64.0% and of GHC plants in the range of 59.1–76.8% of the laboratory oil yield.

The industrial and laboratory oil yield depending on the heating value of dry oil shale for VKG and Kiviõli gas generators are shown in Figure 3.5 and Figure 3.6.

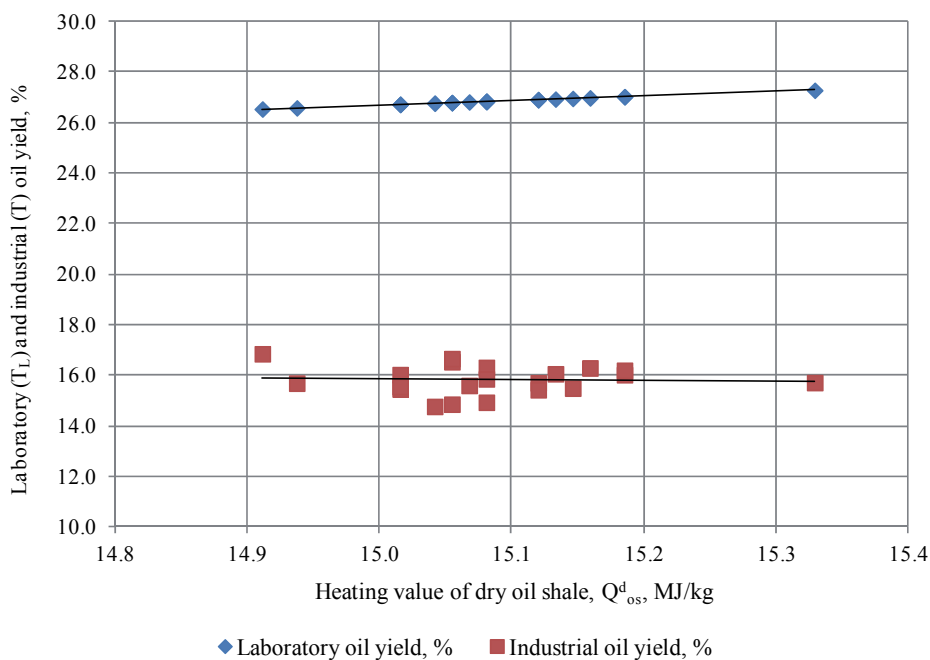


Figure 3.5 Industrial and laboratory oil yield versus the heating value of dry oil shale (VKG gas generators), 1990–2010

The annual average heating values of dry oil shale (in Figure 3.5, Figure 3.6 and Figure 3.6 one dot corresponds to data of one year) come from the model calculations of carbon balance while the laboratory oil yield is calculated using the formula 3.1. As a conclusion, we can say that in 1990–2010 the laboratory oil yield of oil shale from the VKG and Kiviõli gas generators remained in the range of 26.5–27.3% (in VKG) and 18.4–31.2% (in Kiviõli). The actual (industrial) oil yield made from the laboratory oil yield 55.2–63.3% (in VKG) and 53.1–79.6% (in Kiviõli).

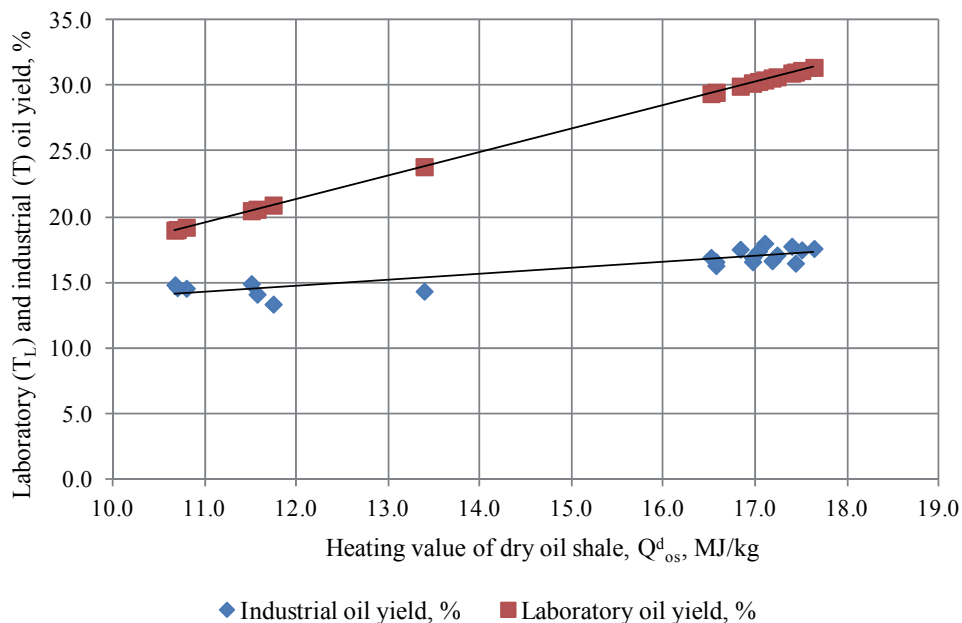


Figure 3.6 Industrial and laboratory oil yield versus the heating value of dry oil shale (Kiviõli gas generators), 1990–2010

Laboratory oil yield from the units with a solid heat carrier Enefit–140 at Narva Oil Plant remained in the range of 17.1–18.1% (industrial oil production made 62.1–73.7% of it) in 1990–2010, that of VKG Petroter unit 17.6% in 2010 and the oil yield of Kiviõli TSK–500 unit was 19.8%. The industrial oil yield made 64% (in VKG) and 62% (in Kiviõli) from the laboratory oil yield. In conclusion, we can say that the industrial oil yield is about a third higher in gas generators (14.6–15.9%) than in the units with a solid heat carrier (10.9–12.3%).

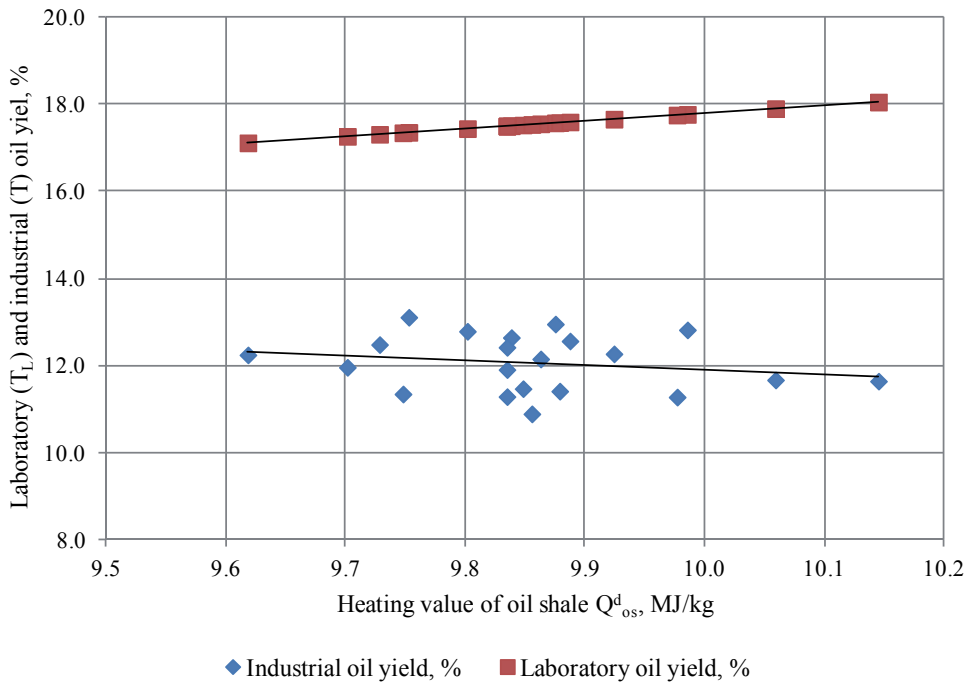


Figure 3.7 Industrial and laboratory oil yield versus the heating value of dry oil shale (Narva Enefit-140), 1990–2010

3.5 Efficiency of oil shale pyrolysis

An important indicator for the shale oil production is the efficiency of utilizing the energy in feedstock oil shale, i.e. the ratio of the energy in shale oil to the energy in oil shale. Basically, this would be a parameter that is known as EROI – energy return on energy invested. Although, the efficiency of production process is characterized by EROI from the position of energy use, it does not include the environmental indicators [34]. So, for calculating the value of EROI it is important to know the amount of heat and electricity needed for oil production, which today, however, is not easily accessible public information. Based on the data received from oil plants, it is still possible give the estimation of this parameter, which can be calculated as the sum of useful energy of the shale oil, semi-coke or generator gas, and that of ash and flue gas cooling divided by the energy entering the process with oil shale.

In Table 3.11 the efficiency of shale oil production by oil plant and technology in 2010 is presented.

Table 3.11 Efficiency of shale oil production by plant and technology in 2010

	Narva Enefit-140	VKG Oil Petroter	Kiviõli SHC-500	VKG Oil gas generators	Kiviõli gas generators
Oil shale, TJ	14 737	2 220	219	21 153	4097
Shale oil, TJ	7 524	1 105	111	10 676	2 595
Semi-coke gas, TJ	2 834	402	32		
Generator gas, TJ				2 736	429
Pyrolysis gasoline, TJ	461	87	10	566	135
Steam production, TJ		71			
Efficiency, %	74	75	70	53	67
Average efficiency by technology, %	74.0			55.3	

In terms of efficiency indicator for oil production or better utilization of the energy in feedstock oil shale, the solid heat carrier technology is considered to be the best.

However, the comparison of indicators presented in Table 3.11 shows that in 2010 the efficiency of the VKG Oil solid heat carrier process Petroter was the highest, approximately 75%, followed by Narva Enefit-140 (74%) and the Kiviõli SHC-500 process approximately 70%.

The efficiency of gaseous heat carrier process in VKG Oil Plant was 53%. In the case of Kiviõli Oil Plant it was approximately 67%, but author of this thesis has serious doubts about the quality of Kiviõli Oil Plant oil shale consumption data of recent years (2005–2010), but it is not possible to check them.

4. GREENHOUSE GAS EMISSION REDUCTION PERSPECTIVES IN ESTONIA

In December 2008, the European Parliament adopted a set of legislative documents – the so called EU climate and energy package for increasing energy supply security and transforming Europe gradually into a low-carbon economy. An agreement has been reached on the following legally binding targets, by 2020:

- to cut GHG emissions by 20% compared to 1990,
- to establish a 20% share for renewable energy in final energy consumption and the share of biofuels up to 10% in transport fuels, and
- to achieve a 20% reduction in energy consumption by 2020 (to improve energy efficiency).

Regarding the reduction of GHG emissions, the package contains an offer to go further and commit to a 30% cut in the event of a satisfactory international agreement being reached [3].

Directive 2009/28/EC sets legally binding targets for each EU Member State, in order to reach the EU aggregated target of a 20% share of renewable energy by 2020. It creates cooperation mechanisms for achieving the targets in a cost effective way. National targets for Member States were set, together with a linear legally binding trajectory for the period 2013–2020 with annual monitoring and compliance checks [35].

Directive 2009/30/EC provides a set of binding targets for the emissions from the fleet of new cars. This is an important tool for meeting emission targets in the non-Emission Trading System (ETS) sectors [36].

Directive 2009/31/EC establishes a legal framework for the environmentally safe geological storage of carbon dioxide (CO₂) to contribute to the fight against climate change [37].

Decision 406/2009/EC lays down the minimum contribution of EU Member States to meeting the GHG emission reduction commitment of the Community for the period from 2013 to 2020 for GHG emissions covered by this decision, and rules on making these contributions and for the evaluation thereof [38].

4.1 Overview of Estonian energy sector

In Estonia the domestic fuels play an important role in the energy supply. The share of these fuels in the primary energy balance has remained at the level of 65–75% during the last decade. Estonia is the only country in the world using oil shale as its major primary source of energy. Estonian oil shale as a fuel is characterised by high ash (45–47%) and sulphur (1.5–1.7%) content, low heating value (8.3–8.7 MJ/kg) and high content of volatile matter in the combustible part (up to 90%) [16]. Wood is another important primary energy resource: more than half of the territory of Estonia is covered by forests. The third important indigenous fuel is

peat. Estonia's dependency on imported energy sources was 21.2% in 2009 [39]. Estonia has no oil-refining capacity, therefore all petroleum products are imported, mainly from Lithuania, Finland and Russia. Nevertheless, Estonia has a long term experience of processing oil shale into shale oil, which is the only locally produced liquid fuel. Estonia has no indigenous natural gas, so it is fully dependent on imports from Russia. In the total primary energy consumption, the share of fossil fuels is very high, approximately 90%.

The Estonian electricity sector is well developed and mainly organised around Eesti Energia AS, which is a state-owned company engaged in power generation and sales throughout the country. There are also some privately owned companies on the market dealing with generation (small-scale combined heat and power generation, mini hydro and wind turbines) as well as with the distribution of electricity. In total, the power plants of Eesti Energia AS generate approximately 91% of the electricity in Estonia [2]. Estonia has always been a net exporter of electricity, mainly to Latvia, but also to Finland, Russia and Lithuania. The only exception was in 2009, when import exceeded the export by 82 GWh.

In 2009, the primary energy supply totalled about 199.8 PJ in Estonia. The major part (81%) of it was utilised in conversion processes. Approximately half (51%) of the converted primary energy was used for electricity generation, and the rest for heat production (24%) and manufacturing secondary fuels, mainly shale oil and peat briquettes (25%). 8% of primary energy was utilised in the energy sector, including the use for non-energy purposes and transmission and transportation losses. About 11% of primary energy went directly to final consumption [1].

4.1.1 Energy efficiency

In Estonia, the efficiency of primary energy utilisation (the ratio of final energy consumption to the primary energy used) is approximately 52% [1], which is lower than in the neighbouring countries. The main factor here is that over 90% of electricity in Estonia is produced in condensing power plants [1]. The efficiency of these plants is very low, approximately 36%. Other factors, like high losses in the power and district heating networks, large export volumes of converted energy, also have an impact.

Much work has been done in the field of energy efficiency in Estonia. A national goal has been set to achieve the continuous improvement of energy efficiency in both the energy conversion and energy end-use sectors. In 2009, the Parliament of Estonia approved the National Development Plan of Energy Sector until 2020 [40]. The Plan foresees that in order to ensure sustainable energy supply and consumption, energy efficiency shall be improved by energy producers, transporters and consumers and the share of renewable energy sources and combined heat and power production (CHP) shall be increased in the energy balance. Upon the development of sustainable energy supply and consumption, the awareness of the public about possible solutions and innovative technologies shall be increased and implementation of new solutions shall be promoted.

In 2005, oil shale formed 45% of the internal (i.e., excluding energy export) energy balance of Estonia. Such a large share of one fossil energy source in the country's energy balance is considered not reasonable due to energy supply security as well as environment considerations. Therefore, it is envisaged to increase the share of other energy sources in the energy balance and to establish the infrastructure for more extensive energy trading with other EU Member States. However, the oil shale power industry shall be developed as well in order to ensure the security of supply.

Regarding the electricity sector, the Plan sets a target to expand the use of CHP up to reaching the share of 20% of gross electricity consumption by 2020. The relevant schemes of operational support for CHP have been introduced. Also, it is foreseen to reduce the losses in power lines below 3% in distribution networks and below 6% in the transmission grid.

From the end of the 2006, a connection has been established with the Finnish energy system through a 350 MW underwater cable Estlink. The new connection increased Estonia's reliability substantially and it enables to export electricity produced in Estonia to the Nordic countries. The construction of the next interconnector (650 MW) between Estonia and Finland – Estlink 2 – is on-going and it is expected to be in operation in 2014.

In order to restrain the increase of energy consumption, it is important to increase the efficiency of the energy system and to promote energy efficiency at end consumers, especially in the heating sector, which has the highest potential for energy conservation. Estonian energy networks have become more efficient: thermal energy losses upon transmission and distribution have decreased by 23% and power energy losses by 28% compared to 2000 [1]. This progress has been achieved by the development of regulation, increased energy prices and sufficient investment capacity of undertakings.

For comparing the energy efficiency levels, both within a country during a time period and between countries, several indicators can be calculated. The most general macro level indicator used for characterizing the overall energy efficiency in a country is the primary energy intensity of the GDP, which relates the total amount of primary energy used in a country to the GDP at constant prices. This indicator represents both the efficiency in the energy transformation sector and that at final consumers.

According to the Eurostat data, the average primary energy intensity in the EU was 3.6 kg oe/1000 EUR in 2009. The corresponding indicator for Estonia was 3.3 times higher. The main reason for the high level of primary energy intensity in Estonia is that over 90% of electricity in Estonia is produced in condensing power plants.

4.1.2 Renewable energy consumption

The use of renewable energy sources in Estonia has been increasing since 1990. The changes of the renewable energy sources share in gross final energy consumption are shown in Figure 4.1.

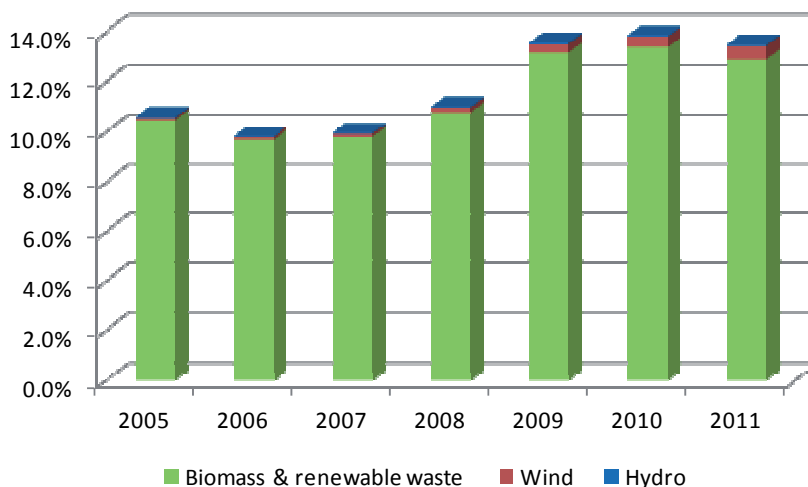


Figure 4.1. Share of renewable energy sources in the gross energy consumption in Estonia [39]

In 2009, 36.2 PJ of renewable energy was produced and 30.0 PJ utilized. The share of renewable energy sources in Estonia's energy balance is rather high: in 2009 the share in primary energy production was 20.8% and in gross inland consumption (GIC) 13.5%. In 2000, the woody biomass was the almost only renewable energy source utilized for energy production.

The deployment of smaller scale CHP as an element of decentralized energy production strategy would increase the energy supply security in Estonia. Therefore, the potential use of biomass in new CHP plants can be a development option. Up to now, the biomass has been fired in district heating and other heat-only boiler (HOB) plants. Today, woody biomass is more widely utilized in district heating plants. In 2010, there were 833 boilers firing wood as a main fuel. Heat production (1557 GWh) by these boilers made up 30.0% of the total heat production in HOB plants. Firewood is also used by households for heating and cooking purposes, especially in rural areas [1].

In Estonia, the heat production in HOB plants is relatively environment benign already. Nevertheless, in the Development Plan 2007–2013 for Enhancing the Use of Biomass and Bioenergy [41] a target was set to increase the share of heat produced from renewable resources in the total volume of district heat from 21% in 2005 to 33% by 2013.

Since 2006, the use of wind energy for electricity generation has grown rapidly, reaching 2.3% of the gross inland consumption in 2009. Regarding electricity production from other renewable sources, there are tens of mini and micro hydropower plants on Estonian rivers generating a minor quantity (ca 30 GWh a year) of electricity while the wind electricity production was 195 GWh in 2009 (277 GWh in 2010). Biomass (woodchips) is utilized in several power plants, in the case of largest plants it is co-fired with oil shale. The new support scheme together with the commissioning of two new CHP plants caused a jump in wood based electricity production from 28 GWh in 2008 to 307 GWh in 2009. In 2009, the total production of renewable electricity reached 541 GWh making 6.1% (1046 GWh in 2010, 10.8%) of the gross electricity consumption in Estonia, meaning that the relevant target set by EU (5.1%) for 2010 was exceeded.

As to other renewable fuels, biogas is produced in small quantities and utilized in some pilot plants. Regarding liquid biofuels, Estonia is in difficult situation as the use of biofuels in transport is so small that it is not reflected in the national energy balance. On the basis of energy content, the biofuels constitute 0.26% of the fuel use in transport. The only national support measure to transport biofuels has been the exemption from excise duty since 2005. The excise exemption permit for biofuels from the EC expired on 27 July 2011.

In 2009, 132 MW of wind power capacity was installed in Estonia, approximately 200 MW of new wind power capacity was constructed and connection points had been completed for an additional capacity of 380 MW. Also, preliminary permits have been given for the installation of 2600 MW of wind power. These projects are still in the planning process. Regarding more extensive use of wind energy, technical limitations are to be considered as the intermittency effects on the grid will need compensating capacity. It was estimated that if these limitations are removed, it will be possible to accommodate up to 1200 MW of wind power with Estlink 1 and up to 2000–2200 MW with both Estlink 1 and Estlink 2 in operation [42].

The current version of the Electricity Market Act provides that the operational subsidies for new wind based electricity will not be paid if the annual production of wind electricity reaches 600 GWh [43]. In projections of wind based electricity it has to be taken in account as well. Assuming the 1100 MW capacity of wind parks by 2020, the annual production may reach 2–3 TWh, which can reduce the CO₂ emission by 1.9–2.8 million tons, in case the oil shale based electricity is replaced.

As to technical potential of biogas, approximately 2.1 million tons of manure with the energy content of 400 GWh is generated annually. If half of it could be used for biogas production, this would form approximately 200 GWh of primary energy. In addition, there are 3–4 sewage treatment plants, whose capacity allows producing biogas that could be utilized on the spot to meet the local needs. Until today, no sufficient resources have been found to produce biogas and sell it into the network in a larger volume.

For promoting the use of renewable energy resources in transport, the following measures are outlined in the National Renewable Energy Action Plan:

- introducing the 5–7% blended fuel obligation on liquid fuels (by 2015);
- transfer of public transport partially (50%) to renewable energy (by 2020);
- encouraging car buyers to prefer environmentally friendly vehicles.

4.2 Greenhouse gas emissions in Estonia

In 2009, the total emissions of GHG in CO₂ equivalent were 9.8 million tons and without land use, the land use change and forestry (LULUCF), 16.84 million tons of CO₂ equivalent. The energy sector is the major source of GHG emissions in Estonia. In 2009, the energy sector contributed about 86% of total emissions, totalling 14.4 Mt CO₂ equivalents. Compared to 1990 as the base year, the emissions were about 60% below that level (36.16 Mt CO₂ eqv.). Most of the energy sector emissions (97.7%) originate from the fuel combustion and only 2.3% are contributed by fugitive emissions. The substantial amount of energy related emissions is caused by extensive consumption of fossil fuels for electricity and heat production. The share of oil shale, shale oil and shale gas combustion is about 67.5% of the energy sector total GHG emissions [44]. The share of oil shale (including secondary fuels made from oil shale: shale oil and shale gas) in electricity production is even larger, being approximately 96% of the electricity production emissions in 2009 [45].

The total GHG emissions can be considered in terms of greenhouse gas intensity of the country's GDP. Intensity shows the amount of emissions for the production of one unit of economic output. The smaller amount of emissions per one euro is emitted, the more environment benign the country's economy is. In 2009, the GHG intensity of Estonia was 1.9 kg CO₂ /EUR, which exceeds the EU average value (0.4 kg CO₂/EUR) by 4.3 times [39, 46].

4.3 Greenhouse gas emission reduction perspectives in Estonia

According to the national GHG inventory 1990–2009 [44], Estonia's emissions have decreased significantly between 1990 and 2009. Since then the annual emissions have stayed more than 50% below the 1990 level. Current analyses and some earlier studies [46] gave a clear indication that Estonia had no problems with meeting the Kyoto targets for 2008–2012.

However, the EU has set several challenging climate and energy targets to be met by 2020. Among these there is a goal to reduce the GHG emissions in the EU Member States by at least 20% below the 1990 level. The reduction of GHG emissions will be achieved through the integration of two mechanisms: the EU Emission Trading System (EU ETS) and country targets for the non-ETS sectors.

In 2009, the European Parliament and the Council adopted a new Directive 2009/29/EC (amending the Directive 2003/87/EU) to improve and extend the

greenhouse gas emission allowance trading scheme of the Community [47]. Nevertheless, when the revised directive governing the EU ETS was adopted in 2009, it was decided to introduce an harmonised EU-wide approach to the allocation of greenhouse gas emission allowances for the installations covered by the system. In particular, it was agreed that during of the ETS third phase (2013–2020), allowances should no longer be granted for free to power plants, which instead would have had to buy all their allowances through auctions (or in the secondary market).

However, to help modernize their electricity sector 10 Member States were given the option (Article 10c of the Directive 2009/29/EC) of exempting these plants from the 'full auctioning' rule and continuing to allocate a limited number of emission allowances to power plants for free until 2019 [47]. These Member States are eligible since they meet one or more of the relevant criteria laid down in the revised EU ETS Directive. These States are: Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland and Romania.

The derogation from full auctioning for the power sector is optional. Eligible Member States need to decide whether they want to make use of this option or not. The Member State needs to decide for how many years and to what extent they want to make use of the derogation, as the Directive defines only maximum values in this regard. Member States applying for the derogation need to take into account that the number of free allowances to be given to the power sector reduces the number of allowances they can sell at auction, thus lowering their national auctioning revenues.

The number of free emission allowances that may be handed out to power plants is limited. The revised ETS Directive stipulates that even when the derogation is granted, the level of free allocation in 2013 must not exceed 70% of the allowances needed to cover emissions for the supply of electricity to domestic consumers. In each year following 2013, this percentage has to decrease gradually – the rules are set out in the Decision – and, in 2020, it has to be 0%. Eligible Member States can decide to distribute fewer free emission allowances than the maximum amount permitted. Free allowances can be given only to power plants that were operational, or for which the investment process was physically initiated, by 31 December 2008. The use of the derogation is not allowed for newer power plants, in order to avoid undue distortion of competition on the European power market [48].

Decision 406/2009/EC lays down the minimum contribution of EU Member States to meeting the GHG emission reduction commitment of the Community for the period from 2013 to 2020 for GHG emissions regulated by this decision, in the sectors covered by the ETS [40]. Here, Estonia is among the 12 Member States with an allowed increase of their non-ETS GHG emissions by 2020. The decision provides that a Member State with a positive limit (i.e., an increase of GHG emissions allowed) shall ensure that its GHG emissions in 2013 do not exceed a

level defined by a linear trajectory, starting in 2009, on its average annual GHG emissions during 2008, 2009 and 2010.

The following formula (4.1) will be applied for calculating the 2020 annual emission allocations for sectors not covered by the EU ETS [49]:

$$(A - B - C - D - E) \times (1 - F) \quad (4.1)$$

where

- A* total emissions, excluding LULUCF in 2005⁶;
- B* CO₂ emissions from the IPCC category ‘domestic civil aviation’ (IPCC CRF 1.A.3) in 2005⁷;
- C* verified 2005 emissions of installations by the ETS in 2005–2007 or verified 2007 emissions of installations by the ETS in 2007⁸;
- D* 2005 emissions of installations that were included or excluded in the ETS in 2008–2012 due to an adjusted scope applied by Member State⁹;
- E* verified 2005 emissions of installations opted out in 2005 and included in the ETS in 2008–2012¹⁰;
- F* emission reduction percentage stated in the ESD (the Effort Sharing Decision – Article 3.2 of the Decision No 4006/2009/EC)¹¹.

Table 4.1 Estonia’s greenhouse gas emission targets for the sectors not covered by the EU ETS in 2020, Mt CO₂

Indicator	2005	2010	2020
Total GHG emissions	19.16	16.84	NO
non-ETS sectors	6.54	6.23	6.92
%	34.10	37.00	37.90

Estonia does not have a fixed national target for the total national GHG emissions up to the year 2020. But, in relation to the commitments agreed at the EU level, Estonia’s GHG emissions from the non-ETS sector should not increase over 11% by the year 2020 compared to 2005. In 2005, the total GHG emissions were 19.2 Mt CO₂ eqv. including 6.5 Mt CO₂ eqv. from the non-ETS sectors and 12.6 Mt CO₂ eqv. from the ETS sector (Table 4.1). The share of non-ETS sectors in the

⁶ Source: National inventory [2]

⁷ Source: National inventory [2]

⁸ Source: Community Independent Transaction Log CITL

⁹ Decisions on national allocation plans for the second commitment period or data notified by the concerned Member States and agreed on by the Commission in the NAP process

¹⁰ Data notified by the concerned Member State

¹¹ Annex II, of the Effort Sharing Decision [38]

country's total emissions is rising (34% in 2005 and 37% in 2009). At the same time, the total GHG emission is decreasing as a result of the measures implemented in the ETS sector [50].

It is not possible to calculate the combined (ETS + non-ETS) volumes of GHG emission for Estonia as at present the national obligations have been set for non-ETS sectors only while the national allocation plans for ETS sectors are still in the preparation phase. For assessing the ability of Estonia to reach the 20% reduction target set by the EU Climate Package, several forecasts are considered. Figure 4.2 presents the actual inventory data for 1990, 2005 and 2009, and forecast data for 2015 and 2020. The forecast data are given for two scenarios: the first one is based on the emission volumes calculated by the Technical University of Athens using the PRIMES model [51]. According to the modelling results, the GHG emissions from Estonia will be 20.4 Mt CO₂ eqv. (Scenario EST 1).

The second scenario (EST 2) has been developed using the national forecasts from the Report pursuant to Article 3 (2) of Decision 280/2004/EC [52]. Here, the 'WM' (with measures) scenario has been selected. The WM scenario assumes that the policy and measures for GHG reduction have been implemented already.

Table 4.2 GHG prognoses to 2020, Mt CO₂ eqv.

Scenarios	1990	2005	2009	2015	2020	Reduction compared to 1990, %
EST 1 ¹²	41.1	19.2	16.8	20.0	20.4	50
EST 2 ¹³	41.1	19.2	16.8	21.1	19.7	52

The emissions calculated for these scenarios are given in Table 4.2. The comparison of results indicates that the prognoses of GHG emissions for Estonia are quite similar, the difference being only 0.7 Mt CO₂ equivalents.

¹² Data source of scenario 1 [50]

¹³ Data source of the scenario 2 [51]

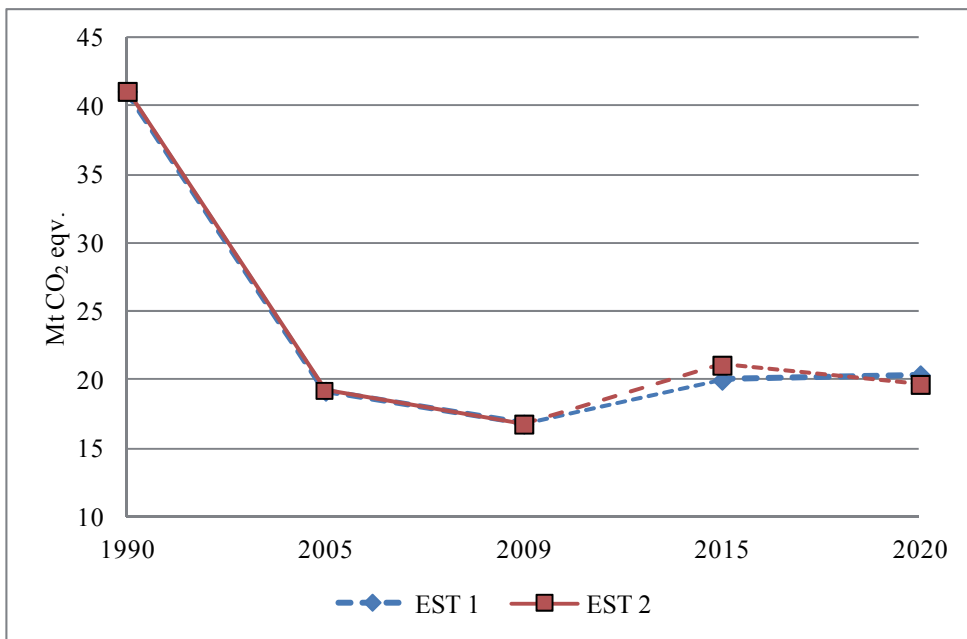


Figure 4.2 Forecast of total GHG emissions in Estonia by different scenarios for the years 2010–2020 (without LULUCF), Mt CO₂ equivalent

4.4 Use of wood for energy generation

One way for reducing greenhouse gas emissions from the energy sector is the wider use of wood fuels for electricity generation in Estonia. The share of wood fuels in the heat production is quite high already, accounting for one third of all the heat produced by boiler plants in 2010. At the same time, the share of electricity production from wood amounted only to 5 percent in 2009 [44].

Use of wood for electricity generation is an essential option for increasing the renewable electricity share at the same time reducing GHG emissions in Estonia. The main advantage of this fuel is that wood is a renewable resource, offering a sustainable and reliable supply. Wood is considered to be carbon neutral.

Wood fuel contains minimal amounts of sulphur and heavy metals. Also, wood is a local fuel in Estonia, and it is usually significantly cheaper than the imported fossil fuels. However, there are some disadvantages of using wood energy. The main disadvantages of wood fuel usage are the high transportation and storage costs [53].

The main factors that influence competitiveness of wood fuel as an energy source for electricity production are Estonian renewable energy support policy, which is based on energy targets and obligations, open electricity market and greenhouse gas (GHG) emission allowance trading mechanisms. The goal of this section is to

evaluate competitiveness of wood fuel in comparison with oil shale taking all these factors into account.

4.4.1 Potential for electricity generation from wood

During a long period the Estonian electricity production has been oriented to oil shale. Before 2009, almost 95% of all electricity was produced from oil shale. But within the last few years the share of renewable energy resources, including the wood fuel, has increased. Nevertheless, it is important to take into account that the potential of wood fuel for electricity production is not yet fully realised.

According to the estimation of the wood fuel resources in Estonia the potential of wood, which can be used for energy production, is 8400 thousand m³ per year (67200 TJ) [54]. Additionally, it is possible to use the woody biomass from the non-forest areas and the wood processing residues. In past years the consumption of wood fuel was less than 4000 thousand m³ per year. From the point of view of wood fuel supply there is an opportunity to double the wood fuel consumption in Estonia. But it is important that there are technological limits for electricity production from wood.

There are three primary technologies used for the electricity generation from wood: direct combustion, pyrolysis and gasification [55]. At the moment, direct combustion is the most appropriate technology, which includes two main opportunities: electricity production in wood-fired cogeneration plants and co-firing with oil shale in oil shale power plants.

Electricity production in wood-fired cogeneration plants is a widely used opportunity to increase the share of renewable energy sources and to reduce the impact on environment [56, 57]. There are three wood-fired cogeneration plants operating in Estonia. In the beginning of 2009, two new plants were put into operation: the Tartu Elektriijaam with capacity of 25 MW_{el} and 52 MW_{th} and the Tallinna Elektriijaam with capacity of 25.4 MW_{el} and 50 MW_{th} [53, 57]. Besides, in the beginning of 2011 a new wood-fired cogeneration plant – the Pärnu Elektriijaam with capacity of 24 MW_{el} and 50 MW_{th} was put into operation. Wood chips and peat can be used as fuel in these plants.

Additionally, there is still a potential for some new wood-fired cogeneration plants. There are few places in Estonia, where the heat load is high enough for an efficient cogeneration. For calculation of the potential, it was assumed that one more wood-fired cogeneration plant would be installed with electrical capacity of 25 MW_{el}.

By feeding the boiler partly with peat, it is possible to keep the boiler burning surfaces cleaner, thus the cogeneration plant can work more efficiently. As regards the peat share in combustion process, the technology allows to be flexible in this point. But peat is considered to be fossil fuel with relatively low heating value and high GHG emissions. From the experience of wood-fired cogeneration plants operating in Estonia, the optimal share of peat is about 10%.

Another possibility for electricity production from wood is the co-firing wood chips with oil shale in power plants in Estonia. Wood co-firing is a well-proven technology which has been successfully demonstrated in more than 200 plants worldwide for most combinations of fuels and boiler types in the capacity range of 50–700 MW_{el} [58].

Two circulating fluidised bed boilers are installed in the Balti and the Eesti Power Plants. Both units have capacity 215 MW_{el} and are flexible for co-firing oil shale with wood. According to different researches and world practice the most suitable co-firing share for wood chips in fluidised bed boilers is 15% [59, 60]. In Estonia, wood chips can be used as an additional fuel in the new oil shale power plant (300 MW_{el}) equipped with circulating fluidized bed technology, which will be built next to an Eesti Power Plant after 2015.

In Estonia, the GHG emission can be reduced by decreasing the share of oil shale and increasing the share of wood. The emission reduction can be calculated as a difference between emissions from the oil shale combustion and the wood combustion, according to the formula (4.2).

$$\Delta GHG = (GHG_{os} - GHG_{wood}), \quad (4.2)$$

where

GHG_{os} – specific GHG emission factor per produced electricity unit for oil shale fluidised bed combustion, tCO₂/MWh_{el};

GHG_{wood} – specific GHG emission factor per produced electricity unit for the wood based electricity production, tCO₂/MWh_{el}.

The value of the carbon emission factor for the oil shale circulating fluidized bed combustion is equal to 26.94 tC/TJ (27.44 tCO₂/MWh_{el}) [33].

A specific CO₂ emission factor per produced energy unit for the oil shale fluidised bed combustion technology is worked out at the Department of Thermal Engineering of the Tallinn University of Technology [61]. The value of the CO₂ emission factor is equal to 0.965 tons of CO₂/MWh_{el}.

According to the international agreement the CO₂ emission from wood combustion is taken equal to zero [62]. There are other GHG emissions such as CH₄ and N₂O, but the amount of these emissions is negligible and it was not taken into account in further calculations.

Therefore, the reduction of the GHG emissions can be calculated by the formula (4.3).

$$\Delta GHG = W_{wood} \times CO_{2\ os}, \quad (4.3)$$

where

$CO_{2\ os}$ – specific CO₂ emission factor of produced electrical energy unit for oil shale fluidised bed unit, tCO₂/MWh_{el};

W_{wood} – annual electricity produced from wood, GWh (formula 4.4).

$$W_{wood} = \sum_{i=1}^n k_i \times P_{CHPi} \times t_i + \sum_{j=1}^m k_j \times P_{CHPj} \times t_j + k_{os} \times P_{os} \times t_{os}, \quad (4.4)$$

where

P_{wood} – installed capacity for electricity production from wood, MW_{el};

P_{CHPi} – installed capacity of existing cogeneration plant i , MW_{el};

k_i – the share of wood used in cogeneration plant i , %;

P_{CHPj} – installed capacity of planned cogeneration plant j , MW_{el};

k_j – the share of wood used in cogeneration plant j , %;

P_{os} – installed capacity of oil shale units, MW_{el};

k_{os} – the share of wood used in oil shale plants, %;

t – operating time, h .

The potential for electricity capacity where wood is used as fuel can be calculated, taking into account the existing wood-fired cogeneration plants, the planned cogeneration plants and the wood fuel resources, which can be used in oil shale power plants by the following formula (4.5).

$$P_{wood} = \sum_{i=1}^n k_i \times P_{CHPi} + \sum_{j=1}^m k_j \times P_j + k_{os} \times P_{os}. \quad (4.5)$$

Results

Taking into account all assumptions and data, which were mentioned in [63] the potential for electricity production from wood in Estonia was calculated. Using the formula (4.5), the total installed capacity for electricity production from wood was calculated. The total capacity that can be installed is close to 200 MW_{el}.

According to the data about the total installed electrical capacity in 2010, the wood based electricity producers could supply 6% from the overall installed capacity.

Table 4.3 Potential of wood based electricity production

Indicator	In existing CHPs	In planned CHPs	In co-firing process	Total
Capacity, MW _{el}	66.96	22.5	109.50	198.96
Electricity production per year, GWh	440.28	146.25	766.50	1 353.03

As it follows from Table 4.3, annual electricity production from wood would reach 1350 GWh, which is approximately 13% from the average total electricity production during the last 5 years.

Wood fuel required for electricity production is about 2000 TWh (7200 TJ). This amount is equal to 10.7% of available wood potential in Estonia, which can be used for energy production.

The avoided GHG emissions were calculated using the formula (4.3). The estimated wood use for electricity production enables the reduction of the GHG emissions from Estonian energy sector by 1.31 Mt of CO₂ per year. It is about 8% from the total greenhouse gas emissions in Estonia. Economic value of this reduction can vary from 13 to 40 MEUR, depending on the actual price for CO₂.

According to the results, the wood fuel can be competitive as a primary fuel for electricity generation when it is used in a cogeneration plant, even when no additional support is provided from the state.

But in the case of wood usage in oil shale units as an additional energy source it is not competitive without the state support for wood based electricity. The reason is that the electricity production costs, when only oil shale is used are much lower, than in the case of wood being added to the co-firing process. It can be explained by high wood fuel prices and relative cheapness of oil shale.

The basic calculations were made for the case when the price of CO₂ emission allowance is 10 EUR/tCO₂. There are no accurate forecasts available for the price of CO₂ emission allowance in 2020. This price can vary in a rather broad range. This factor can influence the results of calculation and this impact should be evaluated by the sensitivity analysis.

CONCLUSIONS

In the first part of the present work the carbon mass balance for thermal processing of Estonian oil shale was investigated. A simplified technology specific calculation method and a model for estimating the carbon amounts leaving the pyrolysis process with products and waste were worked out. The output products considered in the model are: total oil (primary shale oil), oil shale gas (semi-coke gas or generator gas), solid waste (semi-coke and ash) and for the SHC technology – flue gas. The further treatment of primary shale oil is not included in the model since the only carbon re-distribution takes place in the analysed processes¹⁴.

1. The applied carbon mass balance method is the best way for estimating the CO₂ emissions and carbon quantities stored with the products from the thermal treatment of oil shale (shale oil, generator and semi-coke gas) and residues (semi-coke and ash).
2. The values of carbon emission factors for semi-coke gas and generator gas depend on the composition of these gases. The composition of gases depends primarily on the operating mode of the pyrolysis unit and less on oil shale heating value. In 2010, the values of carbon emission factors of semi-coke gas remained in the range of 17.97–18.78 tC/TJ, the weighted average value being 18.77 tC/TJ. Carbon emission factors of generator gas were in the range of 50.36–51.17 tC/TJ, and the weighted average value was 50.52 tC/TJ. Since the value of carbon emission factor is calculated by the gas composition, which depends mainly on the operation mode of the unit and heating value of oil shale, the values of carbon emission factors should be calculated annually.
3. Carbon entering with oil shale the thermal treatment process of the solid heat carrier technology is divided, as follows: 45.0–46.2% leaves the process with shale oil, 11.3–15.5% with semi-coke gas, (which is used as a fuel for electricity and heat production in power plants), 3.1–3.8% with pyrolysis gasoline, 2.4–3.0% with semi-coke and 32.2–36.4% of carbon escapes to the atmosphere with flue gas in the form of CO₂.
4. In the case of oil shale thermal processing in gas generators carbon entering the process with oil shale can be divided by product as follows: 46.4–57.5% leaves the process with shale oil, 23.1–28.4% with generator gas, 2.3–2.8% with pyrolysis gasoline and 16.6–22.8% with semi-coke to the landfill.
5. The carbon dioxide specific emission factor of produced oil is an important indicator for the environmental assessment of various oil production technologies. In this work the CO₂ specific emission factors were calculated for all SHC technology oil plants: Enefit–140 in Narva Oil Plant – 2.13;

¹⁴ Oil shale thermal processing primarily refers to processing or pyrolysis of oil shale. The oil shale chemistry includes basically further processing of raw shale oil for fuel and chemical products [12].

Petroter in VKG Oil Plant – 2.18 and SHC–500 in Kiviõli Oil Plant – 2.45 tCO₂/t. The total weighted average was 2.14 t of CO₂ per ton of shale oil.

6. The correlation between the industrial and laboratory oil yields has also been studied in this work using the oil production actual data of the years 1990–2010. The industrial oil yield of solid heat carrier plants was in the range of 62.1–64.0% and of GHC plants in the range of 59.1–76.8% of the laboratory oil yield.
7. In order to compare the different oil production technologies a special energy efficiency indicator was worked out characterizing the efficiency of utilizing the energy in feedstock oil shale, i.e. the ratio of the energy produced to the oil shale energy used. Energy efficiency indicator of solid heat carrier units is about 75%, the same indicator for gas generators units remains on the level of 55%.

The energy sector is the main contributor to GHG emissions in Europe and in Estonia as well. The Estonian energy generation industry is one of the most CO₂ emission-intensive energy sectors in the EU countries. In Chapter 4 the energy sector of Estonia was analysed from the point of energy efficiency and use of renewable energy sources. All the targets set in the EU Energy and Climate Package were evaluated focusing mainly on reaching the GHG reduction target.

8. Wood fuel use for electricity production provides an essential option for increasing the renewable electricity share and accompanying GHG emission reduction in Estonia. At present, the total installed capacity for electricity production from wood is about 200 MW_{el} in Estonia. These capacities could produce about 1350 GWh of electricity per year. If compared to oil shale based electricity the estimated wood use enables the reduction of GHG emission by 1306 thousand CO₂ tons per year.
9. Research results indicated that wood fuel is not competitive as an additional fuel for electricity production in oil shale units in co-firing process without the state economic support. It means that there is a high risk that electricity producers will stop to use wood after the state support is terminated. It means that CO₂ allowance trading scheme cannot solve the task of wood fuel competitiveness as an additional fuel for electricity generation in oil shale units.
10. On the other hand, calculations of electricity production costs in wood-fired cogeneration plants showed that wood can compete with oil shale as cogeneration plants are more effective, producing and selling both electricity and heat.
11. Based on the GHG emission forecasts described in Chapter 4, it could be concluded that Estonia can meet the targets set by the EU Climate and Energy Package for Member States. Estonia has to find a solution for reducing the high share of oil shale in the fuel consumption. Today, oil shale contributes

almost 68% of GHG emissions from the energy sector. According to the analysed forecasts the GHG emission reduction will be much higher than the EU average target: in Estonia for 50–52%, while the required EU average is 20%.

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ABSTRACT

Current research is focused on two objectives: firstly, to upgrade the methodology for the GHG emission calculation for the Estonian oil shale industry, and secondly, to assess the options for GHG emission reduction of the energy sector as the largest source of pollution and Estonia's ability to comply with the new EU energy and climate policy obligations.

In Estonia, two different shale oil production technologies are in use: the Kiviter type gas generators where the generator gas formed during the process is used as a heat carrier, and technology with a solid heat carrier where the residual retorting product – hot ash from afterburning the semi-coke is the heat carrier. The main difference of the two technologies lies with the feedstock – special requirements to oil shale. While the pyrolysis technology with the gaseous heat carrier uses enriched oil shale with a large lump size (25–125 mm), then unenriched and fine oil shale can be used in the unit with a solid heat carrier, which is the best technology when considering utilization of the resource. In the case of SHC technology, the organic matter is not disposed with semi-coke in the waste dump. The only disadvantage is the CO₂ emission to the atmosphere with the flue gas discharged from afterburning the semi-coke. For gas generators there is no direct CO₂ emission to the atmosphere because it is a closed process and the retorting gases are burned in the same retort and the combustion product is utilized in power plant boilers for electricity and heat production.

One goal of this doctor's thesis is to study the distribution of carbon during thermal processing of oil shale (retorting) and develop a calculation model for computing GHG gas emissions from various technologies for Estonian shale oil. The study is based on the annual average data from oil industries: amount of used oil shale and its heating value, amount of produced oil, its heating value and composition as well as amount of retorting gases generated during the process.

The carbon mass balance method was used for developing the calculation model. The advantage of this model against the carbon dioxide balance method is the higher reliability because the carbon dioxide balance method would require taking into account the oxidation rate, thereby increasing the uncertainty of calculation results. The idea of carbon balance method is based on the fact that all the carbon that enters the process has to leave it with different process outputs. The aim of the work was not only to develop calculation method for computing the carbon dioxide emission to the atmosphere, but also to estimate the quantity of carbon stored with output products (oil and gas) and solid waste (semi-coke and ash).

Because the two oil production technologies are different, the calculation methods for computing the carbon balance also differ. In the case of the solid heat carrier technology, the correction factor for the oil shale heating value due to incomplete decomposition of carbonate minerals during afterburning semi-coke has also been

taken into account when calculating the amount of carbon entering the process with oil shale.

Identification of the value of semi-coke carbonates decomposition rate k_{CO_2} is very important in terms of accuracy of the calculation results. The value of k_{CO_2} is according of the test results in the range between 1.5–2.5.

Plant and technology specific carbon emission factors for semi-coke gas and generator gas have been calculated based on the retort gas composition data collected in oil plants. As the composition of gases depends mainly on the operation mode of retorting unit, the specific emission factors have to be calculated annually.

The results of the work showed that in case of solid heat carrier technology the carbon entering the retorting process with oil shale is distributed in the process outputs as follows: 45.0–46.2% of carbon is stored with shale oil, 11.3–15.5% with semi-coke gas, 3.1–3.8% with pyrolysis gasoline, 2.4–3.0% with ash and 32.2–36.4% of carbon is emitted to the atmosphere with flue gas.

In gas generators carbon entering the retorting process with oil shale is distributed as follows: 46.4–57.5% of carbon is bound with shale oil, 23.1–28.4% with generator gas, 2.3–2.8% with pyrolysis gasoline and 16.6–22.8% is deposited with semi-coke to waste heaps.

The carbon dioxide specific emission factor of produced oil is an important indicator for the environmental assessment of various oil production technologies. In this work the CO₂ specific emission factors were calculated for all SHC technology oil plants: Enefit–140 in Narva Oil Plant – 2.13; Petroter in VKG Oil Plant – 2.18 and SHC–500 in Kiviõli Oil Plant – 2.45 tCO₂/t. The total weighted average was 2.14 t of CO₂ per ton of shale oil.

The correlation between the industrial and laboratory oil yields has also been studied in this work using the oil production actual data of the years 1990–2010. The industrial oil yield of solid heat carrier plants was in the range of 62.1–64.0% and of GHC plants in the range of 59.1–76.8% of the laboratory oil yield.

The results of this doctor's thesis can be used to improve the quality of greenhouse gas inventory at the national level and also for the developing the national allocation programme of CO₂ emission allowances. The quality of guidelines prepared by Ministry of Environment can also be enhanced applying method developed in this work.

The fourth chapter of the work is dedicated to the analysis of Estonian energy production sector as the largest source of greenhouse gases. The energy efficiency level and the use of renewables were analysed to assess the ability of Estonia to meet the national commitments set by the EU new energy and climate policy.

Increasing the share of wood as the most significant source of renewable energy is a good method for reducing the GHG emissions. Research showed that considering

the available wood fuel resource, about 1350 GWh of electricity could be produced from wood avoiding 1306 tons of CO₂ emission per year.

When analysing different scenarios of GHG emissions by 2020, a conclusion can be made that Estonia has no problems with meeting the commitments set by the EU energy and climate policy. According to the calculations, Estonia will be able to reduce the GHG emissions by 50–52% from the 1990 level by 2020 and this is considerably more than the required 20%.

Keywords: oil shale, shale oil, oil shale pyrolysis technologies, greenhouse gases

KOKKUVÕTE

Käesoleva doktoritöö eesmärgiks on hinnata energeetikasektori kui kõige suurema kasvuhooaegade saasteallika heitkoguste vähendamise võimalusi ja Eesti suutlikkust täita EL-i uue energia- ja kliimapoliitikaga sätestatud kohustusi, samuti täiustada kasvuhooaegade arvutamise metoodikat Eesti põlevkiviõlitööstuse tarbeks.

Tänapäeval kasutatakse Eestis kahte erinevat õlitootmise tehnoloogiat: Kiviter-tüüpi gaasgeneraatoreid, kus soojuskandjaks on protsessi käigus tekkiv generaatorgaas, ja tahke soojuskandjaga tehnoloogiat, kus soojuskandjaks on utmisprotsessi jääkprodukt – poolkoksi järelpõletamisest tekkiv kuum tuhk. Oluline erinevus nende kahe tehnoloogia juures on toorainele (põlevkivile) esitatavad nõudmised. Kui gaasilise soojuskandjaga seade vajab rikastatud ja suurema tüki suurusega (25–125 mm) põlevkivi, siis tahke soojuskandjaga seadmes saab kasutada ka rikastamata peenpõlevkivi, mis on ressursi ärakasutamise seisukohast parim tehnoloogia. Samuti ei kaasne tahke soojuskandjaga tehnoloogia korral orgaanilise aine ladustamist koos poolkoksiga jäätmemäkke. Puuduseks on vaid poolkoksi järelpõletamise protsessis tekkivate suitsugaaside koostises oleva süsinikdioksiidi emissioon atmosfääri. Gaasgeneraatorite kasutamise korral CO₂ emissiooni atmosfääri aga ei toimu, kuna tegemist on kinnise protsessiga, kus uttegaasid põletatakse gaasilise soojuskandja saamiseks samas utmisseadmes ja põlemisproduktid utiliseeritakse kateldes elektri ja soojuse tootmiseks.

Käesoleva doktoritöö üheks eesmärgiks oli uurida süsiniku jaotumist põlevkivi termilisel töötlemisel (utmisel) ja koostada mudel süsinikdioksiidi heitkoguste arvutamiseks põlevkiviõli tootmise erinevatele tehnoloogiatele. Uuring põhineb õlitööstustest saadud aastakeskmistel andmetel: kasutatud põlevkivi kogus ja kütteväärtus, toodetud õli kogus ja kütteväärtus ning protsessi käigus tekkinud uttegaaside koostised ja kogused. Arvutusmudeli väljatöötamisel on kasutatud süsiniku massibilansi meetodit.

Süsiniku massibilansi meetodi idee rajaneb põhimõttel, et kogu süsinik, mis läheb põlevkiviga protsessi sisse, peab sealt ka protsessi erinevate väljunditega välja tulema. Töö eesmärgiks ei olnud üksnes utmisprotsessist atmosfääri emiteeritavate süsinikdioksiidi heitkoguste arvutamise metoodika väljatöötamine, vaid ka väljundproduktides (õli ja gaas) ning tahkes jäägis (poolkoks ja tuhk) sisalduva süsiniku koguste hindamine.

Kuna õlitootmise tehnoloogiad on erinevad, siis on erinev ka süsinikubilansi koostamise arvutusmetoodika. Tahke soojuskandjaga seadme puhul on protsessi põlevkiviga siseneva süsiniku koguse väljaarvutamisel võetud arvesse ka põlevkivi alumise kütteväärtuse parandustegurit, mis tuleneb karbonaatmineraalide mittetäielikust lagunemisest poolkoksi järelpõletamisel. Arvustulemuste korrektsuse seisukohalt on väga oluline ka poolkoksi karbonaatide lagunemisastme k_{CO_2} väärtuse arvutamine. Antud töös on k_{CO_2} väärtus arvutatud varasemate

katseandmete põhjal Narva õlitechase tahke soojuskandja (Enefit-140) seadmel. Karbonaatide lagunemisastme k_{CO_2} väärtus võib teistes õlitechastes olla teatud määral erinev, kuid katseandmete puudumisel on töös kasutatud Narva õlitechase k_{CO_2} väärtust ka kõigi teiste tahke soojuskandjaga õlitechaste süsinikubilansi arvutustes.

Gaasgeneraatoritehnoloogia korral on süsiniku koguse arvutamisel kasutatud põlevkivi tarbimisaine alumist kütteväärtust, kuna poolkoksi järelpõletamist ja karbonaatide lagunemist ei toimu.

Õlitechastest kogutud uttegaaside aastakeskmise koostiste baasil on välja töötatud tehnoloogia- ja tehasepõhised süsiniku eriheitetegurid poolkoksigaasile ja generaatorgaasile. Kuna gaaside koostised sõltuvad utteseadme töörežiimist, on vaja igal aastal arvutada antud aasta keskmised eriheitetegurid.

Töö tulemusena selgus, et põlevkiviga utmisprotsessi sisenev süsinik jaguneb tahke soojuskandjaga tehnoloogia korral protsessi väljundites järgmiselt: 45,0–46,2% süsinikust seotakse põlevkiviõliga, 11,3–15,5% poolkoksi gaasiga, 3,1–3,8% gaasbensiiniga, 2,4–3,0% süsinikku ladustatakse tuhaväljadele või aheraine märke ja 32,2–36,4% süsinikku emiteeritakse süsinikdioksiidi kujul koos suitsugaasidega atmosfääri.

Põlevkivi utmisel gaasgeneraatorites jaguneb põlevkiviga protsessi sisenev süsinik aga järgmiselt: 46,4–57,5% süsinikust seotakse põlevkiviõliga, 23,1–28,4% generaatorgaasiga, 2,3–2,8% gaasbensiiniga ja 16,6–22,8% süsinikku ladustatakse koos poolkoksiga aheraine märke.

Süsiniku massibilansside koostamise käigus kogutud ja töödeldud andmete baasil on leitud ka teisi õlitootmist iseloomustavaid indikaatoreid: süsinikdioksiidi eriheide toodetud õli tonni kohta, erinevate õlitootjate tööstuslik õlisaagis ja õlitootmise efektiivsuse näitajad.

Erinevate õlitootmistehnoloogiate hindamisel kasutatakse ühe keskkonnasõbralikkuse näitajana ka süsinikdioksiidi eriheiteteguri väärtust toodangu ühiku kohta. Käesolevas töös on välja arvatud CO_2 eriheiteteguri kaalutud keskmine väärtus tahke soojuskandjaga tehnoloogiale tervikuna – 2,14 tonni CO_2 tonni põlevkiviõli kohta ja eriheiteteguri täpsustatud väärtused õlitööstuste kaupa, mis olid järgmised: Narva Enefit-140 tehnoloogiale – 2,13; VKG Oil Petroter tehnoloogiale – 2,18 ja Kiviõli Keemiakombinaadi TSK 500-le –2,45 t CO_2 /t toodetud õli kohta.

Tuginedes reaalsele õlitoodangu andmetele, on töös uuritud ka põlevkivi tööstusliku ja laboratoorse õlisaagise vahekorda. Antud töö raames tehtud arvutused näitasid, et 2010. aastal moodustas keskmine õlisaagis tahke soojuskandjaga seadmetes 62–64% ja gaasilise soojuskandjaga gaasgeneraatorites 59–77% laboratoorsest õlisaagisest.

Töös on välja arvatud ka põlevkiviõli tootmise efektiivsuse indikaator, mis iseloomustab lähtepõlevkivis sisalduva energia ärakasutamise efektiivsust ehk milline on toodetud energia ja tootmiseks kasutatud energia suhe. Õlitootmise efektiivsuse näitaja poolest on parim lahendus tahke soojuskandjaga tehnoloogia, mille keskmine efektiivsus oli 2010. aastal ligikaudu 74%.

Doktoritöös saadud tulemusi on võimalik kasutada riikliku kasvuhoonegaaside inventuuri kvaliteedi parendamiseks, samuti riiklikus jaotuskavas osalevate ettevõtete süsinikdioksiidi heitkoguste aruannete koostamisel. Töös esitatud meetodika alusel saab tõsta ka Keskkonnaministeeriumi poolt koostatavate juhendmaterjalide kvaliteeti.

Töö neljandas peatükis on analüüsitud Eesti energiatootmise sektorit kui suurimat kasvuhoonegaaside allikat energia efektiivsuse taseme ja taastuvate energiaallikate kasutamise seisukohast ning hinnatud Eesti suutlikkust täita Euroopa Liidu uue energia ja kliimapoliitikaga sätestatud riiklike kohustusi. Puidu kui olulisima taastuva energiaallika osakaalu suurendamine elektri tootmisel on hea meetod kasvuhoonegaaside emissioonide vähendamiseks.

Eesti üldise energiakasutuse efektiivsuse näitaja on üks EL-i madalamaid (2009. a 52%). Riikide energiakasutuse efektiivsuse võrdlemiseks on kasutusel majanduse energiamahukuse indikaator, mis väljendab primaarenergia vajadust toodetud sisemajanduse kogutoodangu (SKT) kohta. Eesti SKT energiamahukus oli 2009. aastal 3,6 korda kõrgem Euroopa Liidu keskmisest näitajast (3,6 kg oe/1000 EUR). Põhjuseks on asjaolu, et ligikaudu 90% elektrist toodetakse Eestis kondensatsioonielektri jaamade abil.

Läbiviidud arvutused näitavad, et arvestades puitkütuse ressursi, oleks võimalik toota puidust ligikaudu 1350 GWh elektrit ja hoida seeläbi ära 1306 tuhat tonni CO₂ emissiooni aastas.

Analüüsides erinevaid kasvuhoonegaaside heitkoguste stsenaariume aastani 2020, võib kokkuvõtteks öelda, et Eestil ei ole probleeme EL-i energia- ja kliimapoliitikaga sätestatud riiklike kohustuste täitmisega. Arvutuste kohaselt suudab Eesti aastaks 2020 alandada kasvuhoonegaaside heitkoguste taset 50–52% võrra 1990. aasta tasemest, mis on tunduvalt rohkem kui nõutud 20%.

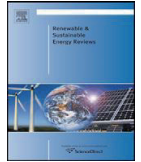
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Greenhouse gas emission reduction perspectives in the Baltic States in frames of EU energy and climate policy

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ABSTRACT

The goal of this paper is to estimate the perspectives of the Baltic States: Estonia, Latvia and Lithuania on meeting the new European Union climate commitments, i.e., to reduce greenhouse gas emissions by 20% to the year 2020 in comparison with 1990. This ambitious target could be reached based on other EU climate and energy package commitments: increase of the share of renewables and improvement of energy efficiency as tools for fulfilling the GHG emissions reduction target.

The paper gives an overview on the current situation and future plans of the Baltic States in the field of energy efficiency, consumption of renewables and reduction of GHG emissions.

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1. Introduction

In December 2008 the European Parliament adopted a set of legislative documents (the so called EU climate and energy package) for transforming Europe gradually into a low-carbon economy and increasing energy security. An agreement has been reached on legally binding targets, by 2020:

- to cut GHG emissions by 20% compared to 1990
- to establish a 20% share for renewable energy in final energy consumption and the share of biofuels up to 10% in transport fuels, and
- to achieve a 20% reduction in energy consumption by 2020 (to improve energy efficiency).

Regarding the reduction of GHG emissions, the package contains an offer to go further and commit to a 30% cut in the event of a satisfactory international agreement being reached [1].

Directive 2009/28/EC sets legally binding targets for each EU member state, in order to reach the EU aggregated target of a 20% share of renewable energy by 2020. It creates cooperation mechanisms for achieving the targets in a cost effective way. Several administrative barriers and other burdens will be removed, confirming the 10% target for renewables in transport, and biofuels sustainability criteria are fixed to ensure that only those biofuels are supported that have no negative environmental impact. The directive also has implications for small-scale emitters in sectors such as transport, buildings, agriculture and waste. By 2020, emissions from these areas are to be reduced by an average of 10% compared to 2005, divided between Member States according to differences in GDP per capita. National targets were set for member States, together with a linear legally binding trajectory for the period 2013–2020 with annual monitoring and compliance checks [2].

Directive 2009/31/EC establishes a legal framework for the environmentally safe geological storage of carbon dioxide (CO₂) to contribute to the fight against climate change [3].

Directive 2009/30/EC provides a set of binding targets for the emissions from the fleet of new cars which is an important tool for meeting emission targets in the non-ETS sectors. The directive sets targets to ensure that emissions from the new car fleet are reduced to an average of 120 g CO₂/km. The long-term target is set to 95 g CO₂/km to be reached by 2020 [4].

Decision 406/2009/EC lays down the minimum contribution of EU member States to meeting the GHG emission reduction commitment of the Community for the period from 2013 to 2020 for GHG emissions covered by this decision, and rules on making these contributions and for the evaluation thereof [5].

2. Background

2.1. Overview of Estonian energy sector

In Estonia the domestic fuels play an important role in energy supply. The share of these fuels in the primary energy balance has remained at the level of 65–75% during the last decade. Estonia is the only country in the world to use oil shale as its major primary source of energy. Estonian oil shale as a fuel is characterised by high ash (45–47%) and sulphur (1.5–1.7%) content, low net calorific value (8.3–8.7 MJ/kg) and high content of volatile matter in the combustible part (up to 90%) [6]. Wood is another important primary energy resource: more than half of the territory of Estonia is covered by forest. The third important indigenous fuel is peat. Estonia's dependency on imported energy sources was 21.2% in 2009 [7] Estonia has no oil-refining capacity, and therefore all petroleum

products are imported to Estonia, mainly from Lithuania, Finland and Russia. Nevertheless, Estonia has a long term experience of processing oil shale into shale oil – a liquid fuel, which is the only locally produced liquid fuel. Estonia has no indigenous natural gas, so it is fully dependent on imports of natural gas from Russia. In total primary energy consumption, the share of fossil fuels is very high, approximately 90%.

The Estonian electricity sector is well developed and mainly organised around Eesti Energia AS which is a state – owned company engaged in power generation and sales throughout the country. There are also some privately owned companies in the market dealing with generation as well as with the distribution of electricity (small-scale combined heat and power generation, mini hydro and wind turbines). In total, the power plants of Eesti Energia AS generate approximately 91% of the electricity in Estonia [8]. Estonia has always been a net exporter of electricity, mainly to Latvia, but also to Finland, Russia and Lithuania. The only time when import exceeded the export by 82 GWh was in 2009.

The structure of primary energy supply in Estonia is shown in Fig. 1.

In 2009, the primary energy supply totalled about 199.8 PJ in Estonia. The major part (81%) of it was utilised in conversion processes. Approximately half (51%) of the converted primary energy was used for electricity generation, and the rest for heat production (24%) and manufacturing secondary fuels, mainly shale oil and peat briquettes (25%). 8% of primary energy was utilised in the energy sector, including the use for non-energy purposes and transmission and transportation losses. About 11% went directly to final consumption [8].

In Fig. 2 final energy consumption by sectors is presented. The biggest energy consumer is households sector – 45%,

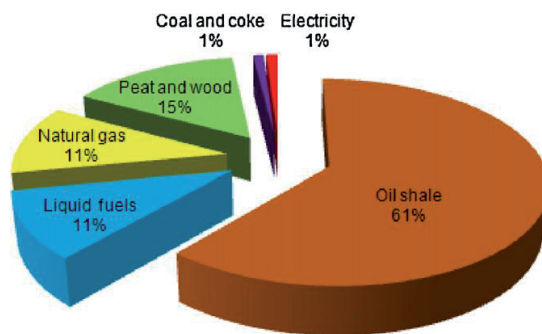


Fig. 1. Primary energy supply in Estonia, % [8].

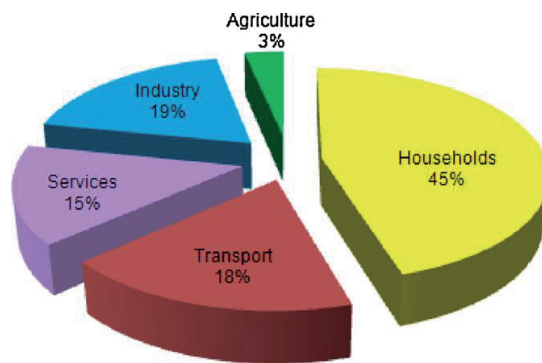


Fig. 2. Final energy consumption in Estonia, % [8].

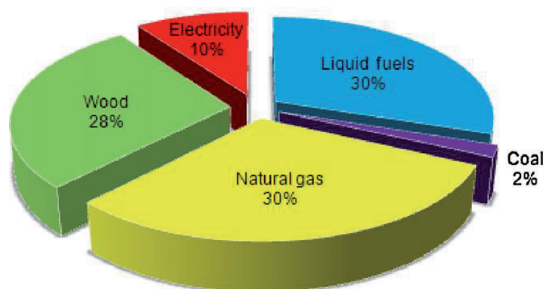


Fig. 3. Primary energy supply in Latvia, % [10].

manufacturing industries, transport and service sectors consume respectively 19%, 18% and 15% and agriculture only 3% of the final energy consumption.

2.2. Overview of Latvian energy sector

Latvia is dependent from imported fossil energy resources and electricity. The most significant domestic energy sources utilised are wood and hydro energy (Daugava Hydropower Plants (HPP) Cascade), but only 29.6% of total energy consumption is covered by these energy resources. Coal, oil products and electricity are imported from different countries (Lithuania, Estonia, Russia), but as in Estonia, there is only one supplier of natural gas – Russia [9].

Within the EU, Latvia has the largest share of renewable energy in its energy mix. Renewable energy sources made up to 36.2% of gross energy consumption in Latvia in 2009. Wood and water are the most widely used renewable energy resources: wood as fuel is used for district heating and heating individual buildings. The share of renewable energy resources in electricity generation is very significant: electricity generation is predominantly based on hydro energy [10]. This electricity comes from three leading hydropower plants in Latvia: the Kegums HPP, Plavinas HPP and Riga HPP. But the volume of electricity generation depends directly on the flow in the River Daugava [11].

The dominant electricity company is the state-owned Latvenergo AS, which imports and generates electricity and controls more than 90% of installed generation capacity, with the balance shared amongst more than 200 small electricity producers. In 2009, Latvenergo AS generated 67% of total electricity supply, 10% was purchased from small electricity producers whilst 23% was the net electricity imports [12].

The structure of primary energy supply in Latvia is shown in Fig. 3.

In 2009, the total primary energy supply was about 189PJ in Latvia. The domestic primary energy production consists mainly of renewable energy: electricity from hydropower plants and fuel wood combustion for heat and electricity production.

The biggest of energy consumers are households, 38% of final energy is consumed by households. 26% of energy is consumed by the transport sector. Fig. 4 shows the final energy consumption by sectors.

2.3. Overview of Lithuanian energy sector

The closure of Ignalina nuclear power plant (NPP) marked a turning point for the Lithuanian energy sector. After shutdown of Ignalina NPP in the end of 2009, Lithuania became dependent on energy and electricity import. Natural gas consumption in its energy mix has increased for the production of electricity

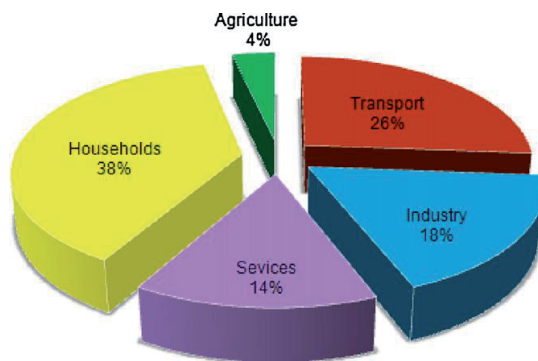


Fig. 4. Final energy consumption in Latvia, % [10].

(Lithuania is totally dependent on natural gas imported from Russia) and the electricity price for customers has increased by more than 30%. Against the background of the economic and financial crisis, the closure of Ignalina NPP is an additional factor, which has affected Lithuania's economic development: the closure of Ignalina NPP alone has reduced Lithuania's GDP growth by at least 1% in 2010. The biggest risk for Lithuania after the closure of Ignalina NPP is the increased dependency on energy imports [13].

The closure of Ignalina NPP led to the revision of Lithuania's national energy policy. It is clear that the closure strengthened the development of other energy infrastructure projects in Lithuania, but Ignalina NPP is not the only reason for these changes. The Baltic Energy Market Interconnection Plan (BEMIP), endorsed on 17 June 2009, is another essential factor for further driving of energy infrastructure projects. The BEMIP, an initiative of the European Commission with 8 participating Baltic Sea countries, is an unprecedented step in the EU energy policy. It creates an energy policy agenda both for generation and interconnection for the Baltic Sea region. The plans to build a new nuclear power plant (Visaginas NPP) together with Latvia, Estonia and Poland in 2020 seem quite real as a strategic investor will be selected in 2011 [14].

2010 was the first year without nuclear power in Lithuania. Currently more than half of the electricity has to be imported. In the field of renewable energy resources Lithuania seeks to achieve the 23% target of renewable energy in the final energy consumption to 2020. This means for the electricity sector that at least 20% has to be covered by renewables. For this purpose, a clear framework and economically most feasible technical solutions should be helpful. In particular, Directive 2009/28/EC has fixed a renewable energy target for electricity of 7% of gross electricity consumption by 2010 [2].

The amount of electricity generation in 2010 has decreased to 4.71 TWh (2009: 13.5 TWh) that means a change of minus 65.1%. About 6 TWh had to be imported, mostly from Belarus (4.09 TWh) and also from Latvia (2.82 TWh) whilst a small amount (0.92 TWh) has been exported to Russia. In 2010 the total Lithuanian electricity demand was covered by fossil fuels for 52% and about 16% (9.6% of the consumed energy) by renewable sources. We have to consider the fact that in 2009 74% of the electricity mix was nuclear power. In particular, the increase of renewable use is only relative and therefore mostly related to the NPP shut-down. For the Lithuanian electricity system, 62% of import was necessary for covering total electricity demand. Lithuania had to import 2–3 times more electricity than any other deficit power system in the EU. Today, Lithuania's most important energy sources are natural gas and oil, each 42%, the full amount out of these sources comes from Russia [15]. Fig. 5 shows primary energy supply in Lithuania in 2009.

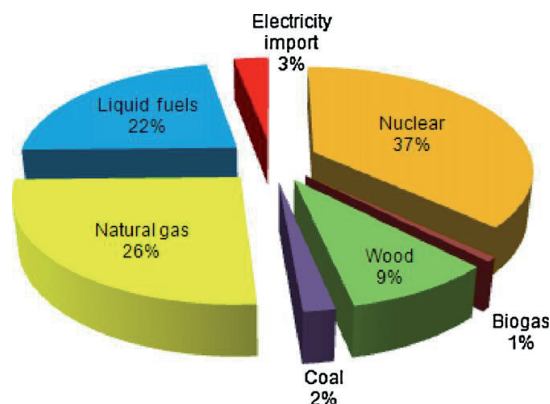


Fig. 5. Primary energy supply in Lithuania, % [3].

The domestic resources represent only about 10% of the primary energy supply of Lithuania.

In 2009, the total primary energy supply was about 356 PJ in Lithuania. The domestic primary energy production consists of nuclear power and renewable energy, including electricity from hydro and wind power plants and fuel wood for heat and electricity production.

The largest energy consumer is the transport sector. 34% of final energy is consumed by this sector and 31% by the household sector. The share of industry is 18% of total final energy consumption. The final energy consumption by sectors is shown in Fig. 6.

Moreover, Lithuania has one of the highest levels of energy intensity amongst the economies in transition. In comparison with the neighbouring Latvia, Lithuanian industry consumes more energy. In recent years, the increase of efficiency in energy consumption has been hampered not only by the limited financial resources, but also by the modest support of the state. In terms of energy intensity and the amount of energy used for producing a unit of GDP, Lithuania is one of the most vulnerable countries in the EU.

2.4. Energy and climate related targets and obligations for the Baltic States

The main climate and energy related targets set in various legal acts of the EU for Estonia, Latvia and Lithuania are listed in Table 1.

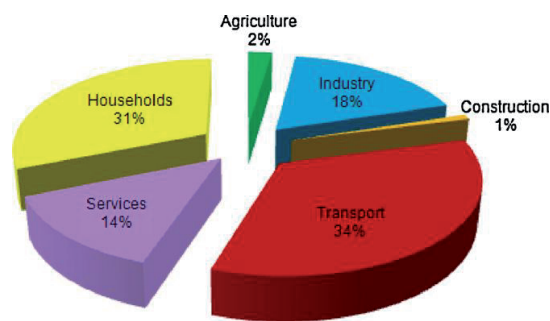


Fig. 6. Final energy consumption in Lithuania, % [15].

Table 1
Renewable energy and climate related targets to the year 2020.

	Estonia	Latvia	Lithuania
Share of RES in the gross final energy consumption [2]	25%	40%	23%
Share of RES in the use of transport fuels [2]	10%	10%	10%
Final energy consumption ^a [16–18]	–11%	–14.5%	–17%
Limit for the non-ETS GHG emissions (compared to 2005) [5]	+11%	+17%	+15%

^a Final energy reduction targets: for Estonia: 11% in comparison with 2010, for Latvia: 14.5% in comparison with 2008 and for Lithuania: 17% in comparison with 2009.

3. Energy efficiency

3.1. Estonia

In Estonia the efficiency of primary energy utilisation (the ratio of final energy consumption to the primary energy used) is approximately 52% [8], which is lower than in the neighbouring countries. The main factor here is that over 90% of electricity in Estonia is produced in condensing power plants [8]. The efficiency of these plants is very low, approximately 36%. Other factors, like high losses in the electricity and district heating networks, large export volumes of converted energy, also have an impact.

Much work has been done in the field of energy efficiency in Estonia. A national goal has been set to achieve the continuous improvement of energy efficiency in both the energy conversion and energy end-use sectors. In 2009 the Parliament of Estonia approved the National Development Plan of Energy Sector until 2020 [19]. The Plan foresees that in order to ensure sustainable energy supply and consumption, energy efficiency shall be improved by energy producers, transporters and consumers and the share of renewable energy sources and combined heat and power production (CHP) shall be increased in the energy balance. Upon the development of sustainable energy supply and consumption, the awareness of the public of the possible solutions and innovative technologies shall be increased and implementation of new solutions shall be promoted.

To attain the objectives of improving energy efficiency, the Energy Conservation Target Programme for the period 2007–2013 has been drawn up.

In 2005 oil shale formed 45% of the internal (i.e., excluding energy export) energy balance of Estonia. Such a large share of one fossil energy source in the country's energy balance is considered not reasonable due to energy security as well as climate considerations. Therefore, it is envisaged to increase the share of other energy sources in the energy balance and to establish the infrastructure for more extensive energy trading with other EU Member States. However, the oil shale power industry shall be developed in order to ensure the security of supply.

Regarding the electricity sector, the Plan sets a target to expand the use of CHP up to reaching the share of 20% of gross electricity consumption by 2020. The relevant schemes of operational support for CHP have been introduced. Also, it is foreseen to reduce the losses in power lines: below 3% in distribution networks and below 6% in the transmission grid.

From the end of the year 2006, a connection has been established with the Finnish energy system through a 350 MW underwater cable Estlink. The new connection increased Estonia's reliability substantially and enables now to export electricity produced in Estonia to the Nordic countries. The construction of the next interconnector (650 MW) between Estonia and Finland – Estlink 2 – is on-going and it is expected to be in operation in 2014.

In order to restrain the increase of energy consumption, it is important to increase the efficiency of the energy system and

energy conservation at end consumers, especially in the heat sector, which has the highest potential for energy conservation. Estonian energy networks have become more efficient: thermal energy losses upon transmission and distribution have decreased by 23% and power energy losses by 28% compared to 2000 [8]. This progress has been achieved by the development of regulation, increased energy prices and sufficient investment capacity of undertakings.

3.2. Latvia

The efficiency of primary energy utilisation in Latvia is approximately 90%. It is much higher than in other countries of the EU. The main reason for that is the fact that significant part of consumed electricity is produced in hydropower plants. Besides, electricity is produced in Riga power plants (TEC 1 and TEC 2) which are partly operating in CHP mode.

The main problems of energy efficiency in Latvia are related with low energy efficiency in the residential and public sectors.

Many energy efficiency measures with positive results have already been undertaken in Latvia. The most effective measures were taken for improving the energy efficiency of buildings and heat supply: replacement and modernization of heating networks, improvement of the heating efficiency of public buildings, installation of more efficient boilers [20].

The government has established a long term vision for Latvia's energy policy through the adopted Guidelines for Energy Sector Development for 2007–2016 [21]. Promotion of energy efficiency has been included in these Guidelines as one of the key priorities for the energy sector development.

According to the requirements of Directive 2006/32/EU [22], Latvia has adopted the First National Energy Efficiency Action Plan (the Plan) for 2008–2010, which includes energy efficiency measures in different sectors showing that the most important actions have to be taken in the household sector [20]. Pursuant to the Plan, various measures are supposed to be realised in Latvia in the residential, industrial and service sectors. The national energy saving target (12.54 PJ) for the period 2008–2016 was calculated. Various measures have been taken in the frame of the Plan: investments in municipal buildings, apartment buildings and district heating systems to increase energy efficiency. The calculations made by the Ministry of Economic Affairs show that during the period 2008–2009 the energy savings in final consumption were 12.30 PJ [23]. The calculations were made taking 2007 for the base year in accordance with the EC requirements.

The new Energy End-use Efficiency Law was adopted in 2010 where the conditions for the development and promotion of a market for energy efficiency services have been defined [24]. According to this law, the Second National Energy Efficiency Action Plan for 2011–2013 was prepared. At the moment this plan is under consideration in the Cabinet of Ministers. The plan includes the measures only for energy end-use efficiency, not for the transformation sector. According to this document, by 2020 the energy savings in total final consumption compared with the base year 2007 should reach 21.78 PJ [25].

3.3. Lithuania

The efficiency of primary energy utilisation in Lithuania is approximately 53%. Although the intensity of primary and final energy consumption has decreased approximately 50% in Lithuania during the period 1996–2009, the energy intensity per unit of GDP is 2.7 times higher than the EU average. This reveals vast untapped potential for energy efficiency, especially in the heating and transport sectors [26].

The positive trends of energy intensity reduction have changed since 2009, because during the crisis of 2007–2009 the energy consumption went down, but for several sectors (services, households, etc.) the energy consumption is less flexible and it has reduced less than GDP. The most energy intensive sectors were the transport and economy sectors [27].

The main policy document to promote energy efficiency in Lithuania is National Energy Efficiency Programme for 2006–2010 approved by the Government in 2007. It sets the following targets: renovation of buildings and updating their energy facilities, increasing energy efficiency of energy production and use in all sectors. Implementation of the Energy Efficiency Action Plan [26] provides for final energy savings up to the amount of 3.9 PJ (1092 GWh)/year in 2010 2.6 PJ (726 GWh/year with earlier actions excluded) and 17.0 PJ (4725 GWh)/year in 2016. This target corresponds to the National Energy Strategy target – starting from 1 January 2008 to achieve 9% of final energy savings during the period of 9 years, compared with the final energy consumption level of 2005. Separate policies and measures are foreseen in the specific sectors of economy. The energy saving targets has been set for specific sectors as well.

According to the National Green Procurement Implementation Programme, the public institutions shall apply environmental criteria for public procurements; at least for 10% of all executed procurements in 2008, 15% in 2009, 20% in 2010 and 25% in 2011. Institutions can choose environmental criteria from the approved list, which also contains the energy efficiency criterion [28]. The Lithuanian Government order for mandatory inclusion of energy efficiency criteria in public procurement was approved in 2008. According to this order, the public institutions shall set minimum efficiency requirements in technical specifications.

In addition, the reduced 9% rate of VAT is applied to the supplies of services related to the construction, renovation and insulation of residential buildings, which are financed from the state and municipal budget resources or with soft credits granted by the state and resources of special state funds.

The Programme of Modernization of Multi-flat Buildings has been an excellent instrument to gain energy intensity decrease in the household and construction sector [27]. The economic crisis had the most painful impact on the construction sector resulting in its shrinkage. Therefore the adequate financing of the renovation of multi-flat buildings would provide for double benefits: recovering of the construction sector and energy intensity decrease in this sector as well as energy intensity decrease in the rest of economy sector. Although Lithuania is currently experiencing some problems with the implementation of Energy Efficiency Action Plan. Main problems are related with the implementation of energy saving targets set for the household sector where the Programme for Modernization of Multi-flat Buildings had failed.

The new financing scheme implemented by the Government with a 50% support of investments instead of 25% would have positive impact on energy savings in the household sector [28]. Other sectors are performing quite well and Lithuania will not face many problems with the requirements set by the EU Energy and Climate Package for energy efficiency improvement to 2020.

3.4. Summary of the Baltic states

For comparing the energy efficiency levels, both within a country during a time period and between countries, several indicators can be calculated. The most general macro level indicator used for characterizing the overall energy efficiency in a country is the primary energy intensity of GDP, which relates the total amount of primary energy used in a country to GDP at constant prices. This

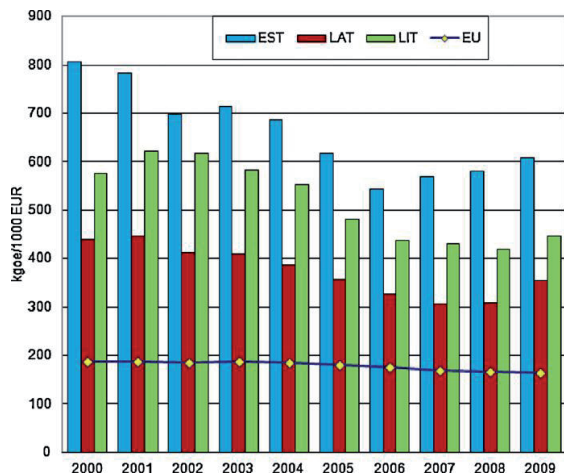


Fig. 7. Primary energy intensity of GDP (EUR CLV2000).

indicator represents both the efficiency in the energy transformation sector and that at final consumers.

According to the latest Eurostat data, the average primary energy intensity in the EU was 3.6 kg oe/1000 EUR in 2009. The corresponding indicators for Estonia, Lithuania and Latvia were 3.6, 2.7 and 2.2 times higher. The lowest level of energy intensity in Latvia can be explained by the fact that electricity in Latvia is produced mostly in hydropower plants and in power plants that partly are operating in CHP mode. The main reason for the high level of primary energy intensity in Estonia is that over 90% of electricity in Estonia is produced in condensing power plants.

The ratio of energy supply to GDP is improving in all three Baltic States: Estonia, Latvia and Lithuania. The lowest value was achieved in 2006; the small increase in the last years was caused by the economic depression (see Fig. 7).

4. Renewable energy consumption

4.1. Estonia

The use of renewable energy sources in Estonia has been increasing since 1990. The changes of the share of renewable energy sources in gross final energy consumption are shown in Fig. 8.

In 2009, 36.2 PJ of renewable energy was produced and 30.0 PJ utilised. The share of renewable energy sources in Estonia's energy

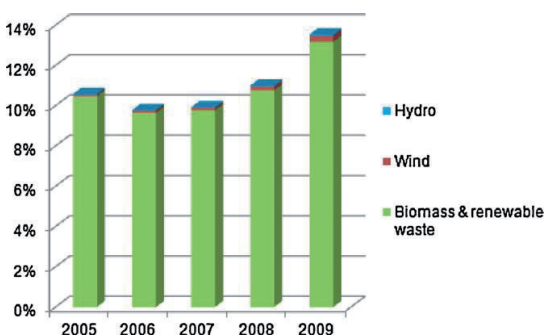


Fig. 8. Share of renewable energy sources in the gross total energy consumption in Estonia, % [7].

balance is rather high: in 2009 the share in primary energy production was 20.8% and in gross inland consumption (GIC) 13.5%. In 2000 the woody biomass was the almost only renewable energy source utilised for energy production.

The deployment of smaller scale CHP as an element of decentralized energy production strategy would increase the energy supply security in Estonia. Therefore, the potential use of biomass in new CHP plants can be a development option. Up to now, the biomass has been fired in district heating and other heat-only boiler (HOB) plants. Today, woody biomass is more widely utilised in district heating plants. In 2010 there were 833 boilers firing wood as a main fuel. Heat production (1557 GWh) by these boilers made up 30.0% of the total heat production in HOB plants. Firewood is also used by households for heating and cooking purposes, especially in rural areas.

In Estonia, the heat production in HOB plants is relatively environment benign already. Nevertheless, in the Development Plan 2007–2013 for Enhancing the Use of Biomass and Bioenergy [29] a target was set to increase the share of district heat produced from renewable resources in total volume of district heat from 21% in 2005 to 33% by 2013.

Since 2006 the use of wind energy for electricity generation has grown rapidly, reaching 2.3% of the GIC in 2009. Regarding electricity production from other renewable sources, there are tens of mini and micro hydropower plants on Estonian rivers generating a minor quantity (ca 30 GWh a year) of electricity whilst the wind electricity production was 195 GWh in 2009 (277 GWh in 2010). Biomass (woodchips) is utilised in several power plants, in the case of largest plants it is co-fired with oil shale. The new support scheme together with the commissioning of two new CHP plants caused a jump in wood based electricity production from 28 GWh in 2008 to 307 GWh in 2009. In 2009 the total production of renewable electricity reached 541 GWh that makes 6.1% (1046 GWh in 2010, 10.8%) of the gross electricity consumption in Estonia, meaning that the relevant target set by EU (5.1%) for 2010 has been exceeded.

As to other renewable fuels, biogas is produced in small quantities and utilised in some pilot plants. No technical quality standards have been established for gas from renewable energy sources, due to which it is not possible to sell it into the network. Similarly, no legislation regulates the sales of gas from renewable energy through the gas network either. As a result, the produced biogas is consumed for local needs and until today the biogas producers have not shown any interest in the production of biomethane.

Regarding biofuels, Estonia is in difficult situation as the use of biofuels in transport is so small that it is not reflected in the energy balance. In the report presented to the EC it is provided that in 2009 four biofuel operators released 1.75 thousand tons (66.98 TJ) of biodiesel and one operator released 0.16 thousand tons (4.28 TJ) bioethanol to the market. On the basis of energy content, the biofuels constitute 0.26% of the fuel use in transport. The only support to transport biofuels has been the exemption from excise duty since 2005. The excise exemption permit for biofuels from the EC expired on 27 July 2011.

At present, 132 MW of wind power capacity is installed in Estonia, approximately 200 MW of new wind power capacity is being constructed and connection points have been completed for an additional approximately 380 MW. Also, preliminary permits have been given for the installation of 2600 MW of wind power. These projects are still in the planning process. Regarding more extensive use of wind energy, technical limitations are to be considered as the intermittency effects on the grid will need compensating capacity. The results of a special study ordered by Estonia's national grid operator Elering AS from the Danish company Ea Energy Analyses a/s indicated that it is technically possible to further develop wind power in Estonia in the coming years without severe balancing costs. If the expansion of the wind power

capacity is limited by the lack of possibility to curtail wind power and the missing regime for allocating balancing cost to the various stakeholders, the wind power capacity should not exceed 600 MW before Estlink 2 is put into operation and 900–1100 MW after Estlink 2 is in operation. It was estimated that if these limitations are removed, it will be possible to accommodate up to 1200 MW wind power with Estlink 1 and up to 2000–2200 MW with both Estlink 1 and Estlink 2 in operation [30].

The current version of the Electricity Market Act provides that the operational subsidies for new wind based electricity will not be paid if the annual production of wind electricity reaches 600 GWh [31]. In projections of wind based electricity it has to be taken in account as well. Assuming the 1100 MW capacity of wind parks by 2020, the annual production may reach 2–3 TWh, which can reduce the CO₂ emission by 1.9–2.8 million tons, if the fossil based electricity is replaced.

As to technical potential of biogas, approximately 2.1 million tons of manure with the energy content of 400 GWh is generated annually. If half of it could be used for biogas production, this would form approximately 200 GWh of primary energy. In addition, there are 3–4 sewage treatment plants whose capacity allows producing biogas that could remain in use on the spot to meet the local needs. Biogas collected from the existing or closed landfills is used either for the needs of the company or to produce heat for the residential district located in the vicinity. Until today no sufficient resources have been found to produce biogas and sell it into the network in a larger volume. In Estonia, during the full harmonisation of Directive 2009/28/EC the issue of biogas integration into the natural gas network will be revised.

For promoting the use of energy from renewable resources in transport, the following measures are outlined in the National Renewable Energy Action Plan:

- establishment of the 5–7% blended fuel obligation on liquid fuels (by 2015);
- transfer of public transport partially (50%) to renewable energy (by 2020);
- encouraging buyers to prefer environmentally friendly vehicles.

In the frame of Green Investment Scheme, there are plans to take use of the revenue from selling CO₂ emission surplus assigned amounts (AAUs) pursuant to the Kyoto Protocol (Article 17). For example, according to the contract signed with Spain, in Estonia 21 MEUR will be invested in new energy efficient diesel fuelled buses (approximately 100 buses for the public sector) where biofuel can be used too.

4.2. Latvia

According to the Eurostat data, Latvia has the highest share of renewable energy in the gross final energy consumption in the European Union. The changes in the share of renewable energy sources are shown in Fig. 9 [7].

Wood fuel and hydro power are mostly used renewable energy sources in Latvia. Wind energy, biogas, biofuels and straw are used in much smaller amounts. The solar energy sources are neither supported, nor used in Latvia. A few exceptions are some projects implemented within the framework of different programmes.

An energy source dominating in renewable electricity is hydropower. The share of hydropower in the total consumption of electricity produced from renewables was 93.6% in 2010 [32]. Hydropower in Latvia includes two groups. First group is three large-scale hydropower plants on the Daugava operated by Latven-ergo AS. These power plants produce approximately 70% of the total electricity volume generated in Latvia. The Kegums HPP installed

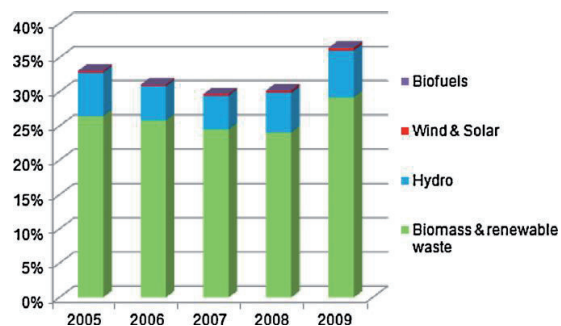


Fig. 9. Share of renewable energy sources in the gross inland energy consumption in Latvia, % [7].

capacity is 240.1 MW, that of Plavinas HPP 883.5 MW and Riga HPP 402 MW [33]. Another group is the small scale hydropower plants. There are 141 small HPPs in Latvia with the total capacity of 26 MW [10,12]. In 2009, these plants produced 66 GWh of electricity. Electricity production in hydropower plants varies strongly along with the natural water supplies.

Latvia has a very good potential for wind energy development alongside the Baltic Sea coastline. The total electrical capacity of installed wind power plants in Latvia was 29 MW at the end of 2009. These plants produced 50 GWh in 2009 and 49 GWh in 2010 [10].

The wind energy potential depends on wind availability in the country. Several studies show that there are three most favourable regions for wind farms in Latvia: a 10–30 km wide breeze zone in Kurzeme (west of Latvia), Kurzeme highlands, Ainaži breeze region with a 15 km zone from the seashore (close to the border with Estonia) [34].

According to the forecast made by Ministry of Economics, the total installed capacity of wind parks will be 416 MW (236 onshore, 180 offshore) in 2020. And according to the assessment presented in the informative report, in 2020 the planned wind power share will make up to 18% of the total electricity from renewable energy sources [32].

At the moment electricity production from biomass is very small in Latvia. There were five biomass fired CHP plants in 2009 with the total installed capacity of 2.95 MW_{el} [33]. But the installation of a new wood-fired CHP plants is planned. In June 2011, there were 29 active licences given by Ministry of Economics for the installation of biomass fired CHP plants with the total installed capacity over 30 MW [12]. The largest wood fired CHP plant in Latvia, which will be installed by the company SIA Graanul Invest, will implement the bubbling fluidized bed technology and use the combination of forest residues, such as bark and wood chips, with milled peat. The capacity of the plant will be 15 MW of heat and 6.4 MW of electricity.

Five biogas power plants with the total installed capacity of 9.1 MW_{el} were also operated in Latvia in 2009. By 2010 six new biogas power plants were installed additionally [33]. According to the Biogas Production and Utilisation Development Programme 2007–2011, the installed capacity of biogas power plants should be about 55 MW by 2011 [35]. In June 2011, there were 59 active licences given by Ministry of Economics for the installation of biogas power plants with the total installed capacity over 13.5 GW [12].

In 2010, heating was dominated by biomass, mainly wood fuel, which comprises 99% of renewable energy sources consumed in the heat supply. The share of heat energy produced using wood fuels was 14.6% [12].

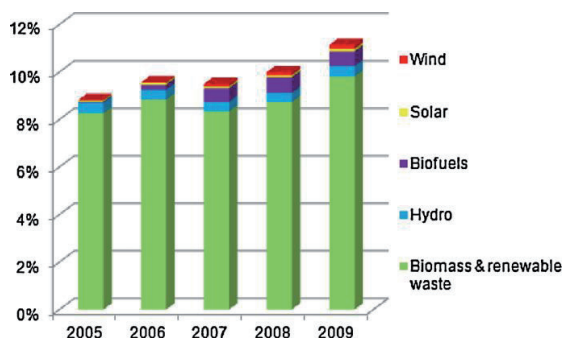


Fig. 10. Share of renewable energy sources in the gross inland energy consumption in Lithuania, %.

There are three main groups of biomass used for heat production in Latvia: wood fuel, straw and agricultural wastes. The most significant group is wood fuel which includes firewood, wood waste and wood products: woodchips and wood pellets. In 2010, 280 boiler houses from 668 used wood as a fuel (140 firewood, 85 woodchips, 11 pellets, 5 wood waste, and 39 mixed biomass fuels). Besides, in 29 boiler houses wood was co-fired with fossil fuels.

The share of straw in heat balance is insignificant—there are only four straw burning boiler houses with the total installed capacity of 5.6 MW operating in Latvia [10].

According to the biofuel production and use in Latvia, this sector is in the development stage. In 2010 two bioethanol production plants and six biodiesel plants were in operation. During a year the share of biofuels in the total amount of transport fuels has risen by 2.48 percentage points to 2.96% in 2010 [36,37]. It can be explained by new amendments in the Cabinet Regulation No. 332 on conformity assessment of petrol and diesel. According to these changes, starting from October 2009, only diesel with biodiesel (obtained from rapeseed oil) content of 4.5–5% by volume of the total quantity of end product is permitted to be sold in Latvia. Additionally, petrol with octane number 95 or higher, but lower than 98, may only be sold if bioethanol content was 4.5–5% (by volume of the sold petrol) [38].

4.3. Lithuania

Lithuania has a scientific, technological and industrial potential for renewable energy development. Despite its small capacity, the renewable energy sector is currently undergoing rapid development. In 2001, renewable energy sector was featured only by wood fuel and hydropower. However, during the past eight years other renewable energy sources have been significantly developed. Wood fuel and wood waste are the most widely used renewable fuels for heating in Lithuania, making up to 90% (the 2009 data). The remaining 13% is other renewables [39].

The biggest renewable potential for electricity production in Lithuania could be considered the hydro and wind energy. It is expected that the usage of biomass in electricity generation will increase nine-fold between 2009 and 2017, whereas the electricity from wind is expected to rise 54 times between 2009 and 2017.

Currently, the share of renewable energy sources in the final energy consumption amounts to around 14%. The largest part of it is covered by biomass, which will continue to play a leading role in the energy production from renewable energy sources. Given Lithuania's natural conditions, the potential of wind and hydro energy is also not fully exploited yet (see Fig. 10).

Electricity generation from renewable energy sources in the energy sector is amongst the state's top priorities. National

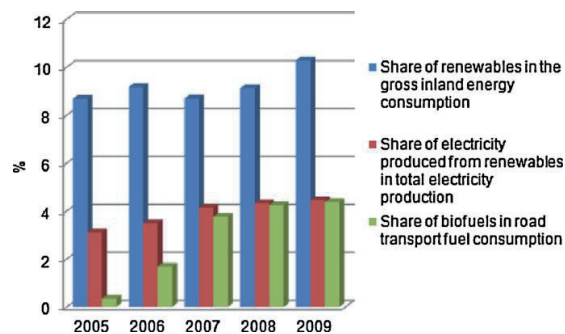


Fig. 11. Development of the use of renewables in Lithuania [15].

Renewable Energy Resources Development Strategy has been approved by the Government [40]. The Strategy defines the main objectives for the energy sector, setting national targets for the implementation of strategic initiatives through the years 2020, 2030 and 2050. The main goal of the Strategy is Lithuania's energy independence before the year 2020. It sets a target to increase the use of renewable energy resources in energy sector from 15.3% in 2008 to 23% in 2020. Lithuania will progressively increase the use of renewable energy resources in the production of electricity and heat as well as in the transport sector. The state will aim to reach the target of 23% of renewable energy in final energy consumption to 2020, including no less than 20% of renewable energy in the electricity sector, 60% in the district heating sector and 10% in the transport sector. The major focus is put on the use of biomass in CHP plants and application of wind power. A priority is also put on the full implementation of available hydro energy potential. The state will aim for at least 20% of electricity to be generated from renewable energy sources, mainly in biomass CHP plants and wind power plants. In order to reach this goal, Lithuania will have to install 500 MW of wind energy capacity, 10 MW of solar energy, at least 224 MW of biomass and 153 MW of hydro energy capacity [41].

Renewable energy sources will cover at least 60% of district heating, mainly by unlocking the biomass potential. In this regard, it is very important to ensure the availability of sufficient biomass resources at competitive prices. The infrastructure for collecting wood biomass will be developed, proper management of the flows of wood products provided and the use of straw substantially increased.

The changes of the share of renewable energy sources in gross final energy consumption and electricity production and that of biofuels in the road transport fuels consumption is shown in Fig. 11.

Fig. 11 shows, that the share of renewables has sharply increased since 2005. The use of renewable energy sources in the transport sector has increased especially drastically.

The Law on Electricity provides that the state shall encourage the producers to generate electricity from renewable energy sources by imposing the public service obligations. In addition to these services, it includes the production of electricity from renewable energy sources connected to the electricity networks [42]. In 2008 the Commission approved the new purchase prices of green electricity, applicable from January 1, 2009. The tariffs will be guaranteed until December 31, 2020. However, several barriers exist, like long lead-times for authorisation, environmental impact assessment procedures, and changes in the legal status of land.

The on Excise Duty provides that the exemption from excise duty is applied to electricity produced from renewable energy sources. The provisions dealing with electricity of the Law on Excise Duty entered into force from January 1, 2010 [43].

A new law on the promotion of renewables was adopted in 2010. The law sets a legal basis for the state management, regulation, supervision and control in the use of renewable energy sources in the energy sector. The provisions of the law regulate relationship between the network operators, energy producers using renewable energy sources and public institutions responsible for maintaining the supervision and control of the use of renewables in electricity, heat and fuels production.

There are no policies or funds for the promotion of renewable energy specific to the industry, only general industrial policies. From 2002 onwards, according to the Law on Taxes for the Pollution of Environment, natural persons and legal entities (industry, district heating companies) implementing environmental protection measures that reduce pollutant emissions into the atmosphere from stationary pollution sources for at least 5% calculated from the highest fixed permitted pollution standard, shall be exempt from the pollution charge under the established procedure if the pollutant amount is reduced by 5% [44].

Lithuania has a vast potential of wood-based fuels, as 31% of the country is covered by forest. As a result, the biomass (wood residues, straw, energy plants), is one of the most significant renewable energy sources, which comprises an important part of the domestic fuel supply. This can be estimated as a total wood stock of 378 million m³, whilst the annual felling volume of wood is 6 million m³. The consumption of wood fuel and wood waste as a fuel makes around 3.7 million m³. Wood accounts for 6% of the total energy produced in Lithuania. Most wood fuel is sawmill waste. Lately, forestry has started selling the logging waste and increasing number of boiler operators use it for fuel. The available resource of forest residues is around 1 million m³. In order to consume this amount in one year, the total capacity of 300 MW boilers would be required [44].

The biofuel penetration has almost doubled between 2006 and 2007. Biofuels are supported through tax exemptions and/or reduction and compensation for raw materials. These measures are potentially sufficient to reach the targets for 2010, but it is not possible to evaluate the impact towards the 2020 targets. They are certainly not sufficient for developing a low carbon economy. There is a lack of legislative framework and coordination, and no incentives for electric transport [45].

Around 1 million tons of industrial and household waste is formed in Lithuania each year. The biodegradable waste compounds make 50% of that amount. Separated biodegradable waste could be used for the production of energy with the annual biogas production potential of 87.4 million m³ (1.9 PJ). To date, less than 10 biogas power plants operate in Lithuania and recycle city sewer sludge, pig manure and a variety of organic waste. The majority of them use biogas to produce electricity. In 2009 biogas composed only 0.05% of total energy amount produced in Lithuania. This sector has a great potential for the development in the future, especially now when the feed-in tariffs have been approved at EUR 0.086 per kWh tariff and the Lithuanian Association for Biogas has been established [45].

Hydropower resources that are available in Lithuania total 2.7 TWh per year. 8% of the hydropower energy comes from two major rivers – the River Nemunas and River Neris. Currently there is only one large-scale HPP in Lithuania located on the River Nemunas in Kaunas. It has a total capacity of 100 MW and total output of 375 GWh per year. To date, more than 80 small HPP have been already built or are under construction. Their total capacity exceeds 14 MW and production amounts reach approximately 540 GWh of electricity per year. However, only 14% of available hydropower resources are being used. This is only 0.3% of total energy production in Lithuania. There are about 130 possible locations for building or renovating small hydropower plants in Lithuania, with a total possible power production up to 60 GWh per year [46].

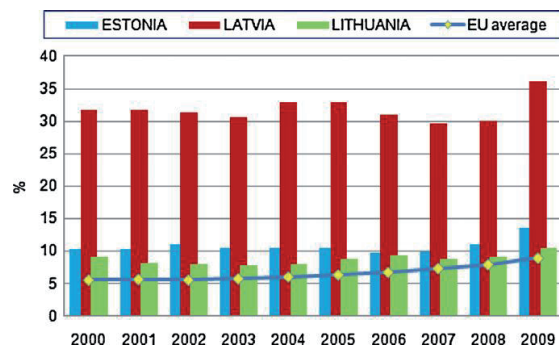


Fig. 12. Share of renewable energy sources in the gross inland energy consumption in Baltic States and EU average, %.

The Government of Lithuania is promoting wind energy, which is one of the cleanest sources for producing electricity. For example, Lithuania participates in a power project aimed at creating proper conditions for efficient development of wind power production in the Baltic Sea region. In 2008, the total capacity of 36 wind power plants that operate in Lithuania was 52.3 MW. The wind based energy production amounts to 1% of the total electricity produced in Lithuania. Lithuania plans to implement off-shore wind power projects in its territorial waters. Unfortunately, the coastline is only 99 km and allocated for various types of use. The Strategic Committee for Energy made a decision that wind power facilities in the sea will be developed starting from 2010 [13].

Geothermal energy in Lithuania is produced from a water basin horizon at the depth of up to 100 m in Klaipėda and Vilnius. In 2009, 9 GWh of geothermal energy was produced in Lithuania amounting to 0.013% of the total energy produced in Lithuania. The geothermal energy for heating private houses can be produced by installing heat pumps. At a depth of 1–1.3 m, the pipes are installed for energy collection. 8% of the required heat energy of households could be produced this way. The geothermal electric energy can be produced from a hot dry rock available only in Western Lithuania at the depth of 2.5–4.5 km.

Lithuania receives 1.0 MWh/m² (total: 65 TWh) of solar energy per year. But more than 80% of it is distributed during 6 months: from April till September. There are some small private installations that use the solar energy for their own needs; however, at present there are no large photoelectric power plants operating in Lithuania. Due to Lithuania's geographical location, seasonal, daily, and meteorological changes, it is not expected that a great part of electricity demand would be met from solar electricity [13].

4.4. Summary of the Baltic states

Regarding the share of renewable energy in the gross inland energy consumption in each of the Baltic States is very different. Including a large hydro input, Latvia has the highest share of renewable energy in the European Union – 36.2% of energy is produced from renewables. In Estonia and Lithuania the use of renewable energy sources has been increasing since 1990, forming in 2009, 13.6% and 10.5% respectively (see Fig. 12)

5. Greenhouse gas emissions in The Baltic States

The total GHG emissions can be considered in terms of greenhouse gas intensity of the country's GDP.

In Fig. 13 the greenhouse gas emission intensity of economy is presented. Intensity shows the amount of emissions emitted for the

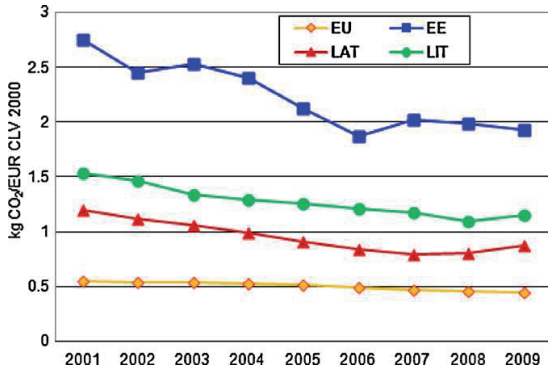


Fig. 13. GHG intensity of economy in 2001–2009.

production of one unit of economic output. The fewer amount of emissions per one euro are emitted, the more environment benign the country's economy is. In 2009, the GHG intensity of Estonia was 1.9, that of Latvia 0.9 and Lithuania 1.2 kg CO₂/EUR; it exceeds the EU average value (0.4 kg CO₂/EUR) 4.3, 2.0 and 2.6 times, accordingly [7,47–49]. At the same time the reduction in the GHG intensity of economy has improved the fastest in Estonia (33%), then in Lithuania (25%), Latvia (28%) and EU average (19%) compared to 2000, which fosters decoupling of emissions from the energy use and economic growth.

5.1. Estonia

In 2009, the total emissions of GHG in CO₂ equivalent were 9.8 million tons and without Land Use, the Land Use Change and Forestry (LULUCF), 16.84 million tons of CO₂ equivalent. The energy sector is the main source of GHG emissions in Estonia. In 2009, the energy sector contributed about 86% of total emissions, totalling 14.4 Mt CO₂ equiv. Compared to the base year 1990, the emissions were about 60% below that level (36.16 Mt CO₂ equiv.). Most of the energy sector emissions (97.7%) originate from fuel combustion and only 2.3% are contributed by fugitive emissions. The substantial amount of energy related emissions is caused by extensive consumption of fossil fuels for electricity and heat production. The share of oil shale, shale oil and shale gas combustion is about 67.5% of the energy sector total GHG emissions (Fig. 14) [50].

The share of oil shale (including secondary fuels made from oil shale: shale oil and shale gas) in electricity production is even larger totalling about 96% of the electricity production emissions in 2009 (see Fig. 15).

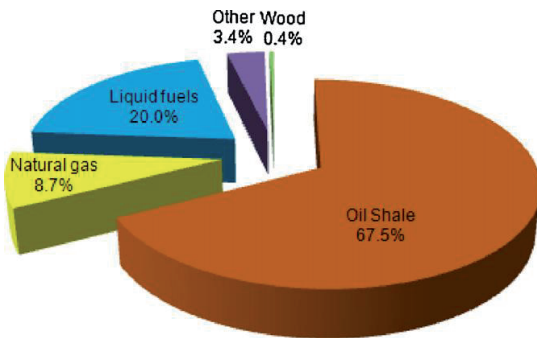


Fig. 14. GHG emissions by sources in 2009, %.

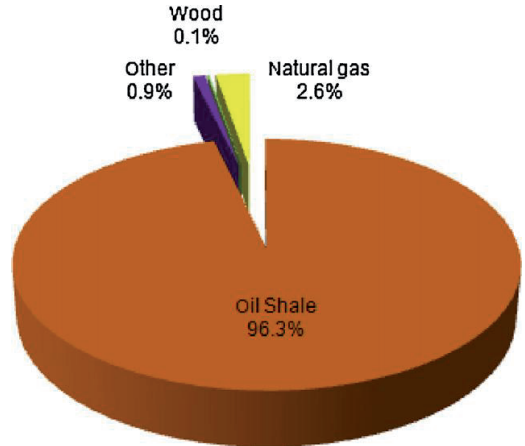


Fig. 15. GHG emissions by fuels in electricity production in 2009, %.

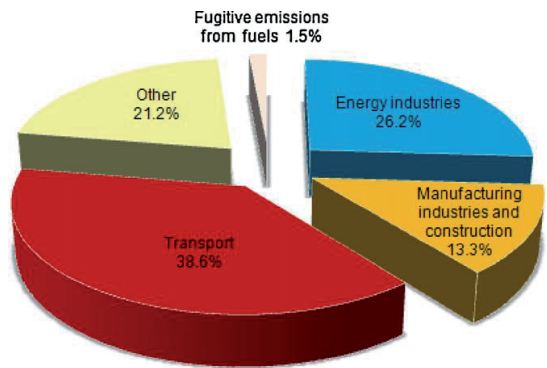


Fig. 16. Emissions from the Latvian energy sector in 2009.

5.2. Latvia

In Latvia the energy sector is the most significant source of GHG emissions too. In 2009, its share in total emissions made 67.4%, totalling 7.09 million tons of CO₂ equivalent. Compared to the base year (1990) the emissions decreased by approximately 62% from that level (18.82 Mt CO₂ equiv.). The largest share of GHG emissions in the energy sector comes from the transport sector (38.6%). 26.18% of energy related emissions originate from industry and 21.18% from other sectors (see Fig. 16).

The evaluation of energy sector key categories showed that the main source of CO₂ emissions is natural gas combustion in the heat and electricity plants. 15.86% of total GHG emissions in the country originate from these plants. The second key source of CO₂ emissions is consumption of diesel oil in the road transportation sector. The diesel oil vehicles have become more popular, because diesel oil is cheaper than gasoline [51].

5.3. Lithuania

In Lithuania, the total emissions of GHG were 17.86 million tons of CO₂ equivalent and without LULUCF 21.61 Mt CO₂ equiv. The energy sector is the most significant source of GHG emissions. In 2009, its share in total emissions comprised 66.5%, totalling 11.9 Mt of CO₂ equivalent. Compared to the base year 1990, the emissions in

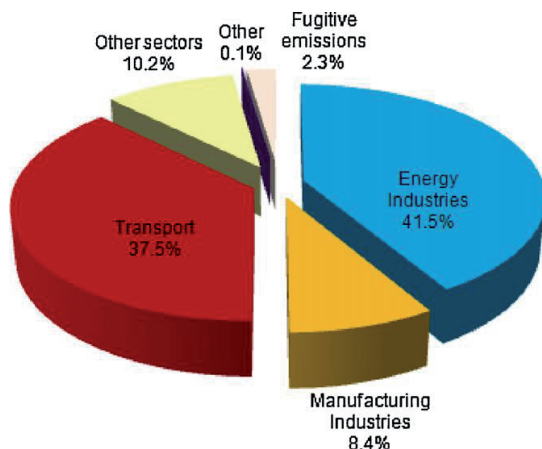


Fig. 17. Emissions from the Lithuanian energy sector in 2009, %.

energy sector have decreased by approximately 65% from that level (33.7 Mt of CO₂ equiv.). The largest share of GHG emissions in the energy sector comes from the transport (38.6%). 26.18% of energy related emissions originate from industries and 21.18% from other sectors (see Fig. 17) [52].

6. Greenhouse gas emissions reduction perspectives in the Baltic States

According to the National GHG Inventories, Estonia's, Latvian's and Lithuania's emissions decreased significantly between 1990 and 2009. Since then the annual emissions stayed more than 50% below the 1990 level. Current analyses and some earlier studies [53] give a clear indication that the Baltic States have no problems with meeting their Kyoto targets for 2008–2012 (see Fig. 18).

However, the EU has set several challenging climate and energy targets to be met by 2020. Amongst these there is a goal to reduce the GHG emissions in the EU member States by at least 20% below the 1990 level. The reduction of GHG emissions will be achieved through the integration of two mechanisms: the EU Emission Trading System (EU ETS) and country targets to the non-ETS sectors.

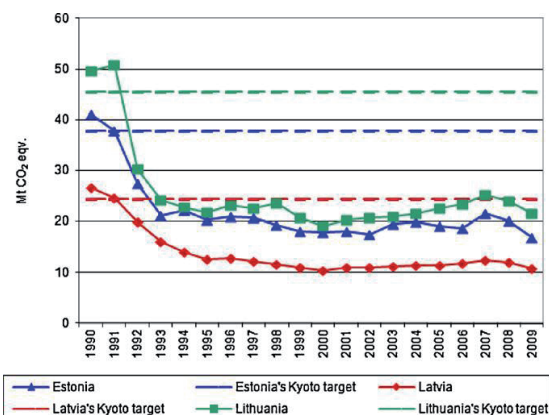


Fig. 18. Kyoto targets and trends of GHG emissions for Estonia, Latvia and Lithuania, Mt CO₂ equivalent.

In 2009 the European Parliament and the Council adopted a new Directive 2009/29/EC (amending the Directive 2003/87/EU) to improve and extend the greenhouse gas emission allowance trading scheme of the Community [54]. Nevertheless, when the revised directive governing the EU ETS was adopted in 2009, it was decided to introduce a harmonised EU-wide approach to the allocation of greenhouse gas emission allowances to the installations covered by the system. In particular, it was agreed that from the beginning of the ETS third phase (2013–2020), allowances should no longer be granted for free to power plants, which instead would have had to buy all their allowances through auctions (or in the secondary market).

However, to help modernize their electricity sector 10 new Member States were given the option (Article 10c of the Directive 2009/29/EC) of exempting these plants from the 'full auctioning' rule and continuing to allocate a limited number of emission allowances to power plants for free until 2019.

The eligibility criteria for exception are as follows:

- in 2007, the Member State had no connection to the electricity grid operated by the Union for the Coordination of Transmission of Electricity (UCTE) which existed then; or
- in 2007, the Member State had only one direct or indirect connection to the electricity grid operated by UCTE with a capacity of less than 400 MW; or
- in 2006, more than 30% of the electricity generation in the Member State concerned was produced from a single fossil fuel and the GDP per capita (at market prices) did not exceed 50% of the EU average.

Ten Member States are eligible since they meet one or more of the relevant criteria laid down in the revised EU ETS Directive. These States are: Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland and Romania.

The derogation from full auctioning for the power sector is optional. Eligible Member States need to decide whether they want to make use of this option or not. The Member State needs to decide for how many years and to what extent they want to make use of the derogation, as the Directive defines only maximum values in this regard. It must submit an application to the European Commission by 30 September 2011. Member States applying for the derogation need to take into account that the number of free allowances to be given to the power sector reduces the number of allowances they can sell at auction, thus lowering their national auctioning revenues.

The number of free emission allowances that may be handed out to power plants is limited. The revised ETS Directive stipulates that even when the derogation is granted, the level of free allocation in 2013 must not exceed 70% of the allowances needed to cover emissions for the supply of electricity to domestic consumers. In each year following 2013, this percentage has to decrease – the rules are set out in the Decision – and, in 2020, has to be 0%. Eligible Member States can decide to distribute fewer free emission allowances than the maximum amount permitted. Free allowances can be given only to power plants that were operational, or for which the investment process was physically initiated, by 31 December 2008. The use of the derogation is not allowed for newer power plants, in order to avoid undue distortion of competition on the European power market [55].

Decision 406/2009/EC lays down the minimum contribution of EU member States to meeting the GHG emission reduction commitment of the Community for the period from 2013 to 2020 for GHG emissions regulated by this decision, in the sectors covered by the ETS [5]. Here, Estonia, Latvia and Lithuania are amongst the 12 member States with an allowed increase of their non-ETS GHG emissions by 2020. The decision provides that a member state with

Table 2
Greenhouse gas emission targets of the sectors not covered by the EU ETS in 2020, Mt CO₂ equiv.

	2005	2009	2020
Total GHG emissions in Estonia	19.16	16.84	
Non-ETS	6.54	6.23	6.92
%	34.1	37.0	37.9
Total GHG emissions in Latvia	11.42	10.72	12.20
Non-ETS	8.57	8.23	10.01
%	75.0	76.8	82.1
Total GHG emissions in Lithuania	22.61	21.61	
Non-ETS	16.0	15.8	18.7
%	70.8	73.1	69.5

a positive limit (i.e., an increase of GHG emissions allowed) shall ensure that its GHG emissions in 2013 do not exceed a level defined by a linear trajectory, starting in 2009, on its average annual GHG emissions during 2008, 2009 and 2010.

The following formula (1) will be applied for calculating the 2020 annual emission allocations for sectors not covered by the EU ETS [56]:

$$(A-B-C-D-E) * (1+F), \quad (1)$$

where *A* is the total emissions, excluding LULUCF in 2005¹; *B* is the CO₂ emissions from the IPCC category domestic civil aviation (IPCC CRF 1.A.3) in 2005²; *C* is the verified 2005 emissions of installations by the ETS in 2005–2007 or verified 2007 emissions of installations by the ETS in 2007³; *D* is the 2005 emissions of installations that were included or excluded in the ETS in 2008–2012 due to an adjusted scope applied by Member State⁴; *E* is the verified 2005 emissions of installations opted out in 2005 and included in the ETS in 2008–2012⁵; *F* is the emission reduction percentage stated in the ESD (the Effort Sharing Decision – Article 3.2 of the Decision No. 4006/2009/EC)⁶.

Estonia does not have a fixed national target for total national GHG emissions up to the year 2020. But, in relation to Estonia's commitments agreed at the EU level, Estonia's GHG emissions from the non-ETS sector should not increase over 11% to the year 2020 compared to 2005. In 2005 the total GHG emissions were 19.2 million tons of CO₂ equivalent, including 6.5 million tons of CO₂ equivalents from the non-ETS sector and 12.6 million tons of CO₂ equivalents from the ETS sector (Table 2). The share of non-ETS sector in the country's total emissions is rising (34% in 2005 and 37% in 2009). At the same time, the total GHG emissions are decreasing as a result of the measures implemented in the ETS sector [16].

Latvia's target is to limit the total national GHG emissions so that in 2020 they would not exceed 12.19 Mt CO₂ equiv. The target for GHG emissions in the non-ETS sector in 2020 is taken equal to the maximum limit +17% compared to 2005 allowed with Decision 406/2009/EC. The structure of Latvia's emissions has several peculiarities that should be taken into account when planning further measures of emission reduction. The ETS as an emission reducing mechanism covers only 23% of Latvia's GHG emissions, which is the second lowest share in the EU. And required limit +17% for non-ETS sector can be reached in case total GHG emissions will reduce by 56% compared to 1990. Such non-ETS sectors

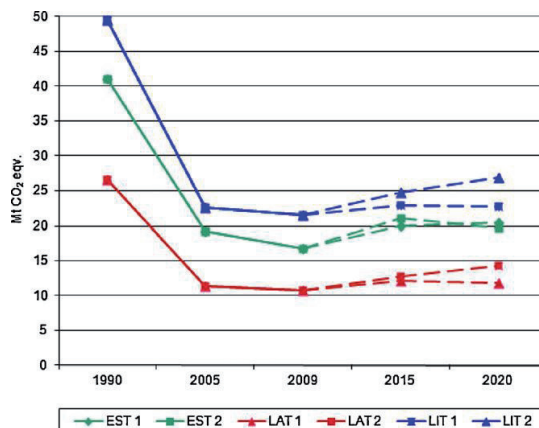


Fig. 19. Forecast of total GHG emissions in Estonia, Latvia and Lithuania by different scenarios for the years 2010–2020 (without LULUCF), Mt CO₂ equivalent.

as the small-scale energy production, small industry, transport, agriculture, households and waste sector are of key importance in the reduction of overall emissions of Latvia. Moreover, 62% of emission structure in the abovementioned non-ETS sectors is comprised of sources in transport and agriculture that cannot be easily influenced. Other non-ETS sectors where the emissions are usually decreased by the measures for fuel changes environmentally friendly fuels – wood and natural gas are widely used already [17,57].

Lithuania is permitted to increase its greenhouse gas emissions by no more than 15% until 2020, compared to the 2005 level, in the sectors that are not covered by the ETS [18]. In 2005, all sectors in Lithuania emitted 22.6 million tons of CO₂ equivalent: 6.6 million tons were emitted from the installations participating in the EU ETS whilst 16 million tons of CO₂ equivalent were emitted in the sectors not covered by the EU ETS. In 2009, 15.8 million tons of CO₂ equivalent were emitted in the sectors not covered by the EU ETS (the permissible amount until 2020 is 18.7 million tons of CO₂ equivalent).

It is not possible to calculate the combined (ETS+non-ETS) volumes of GHG emission for the Baltic States as at present the national obligations have been set for non-ETS sectors only whilst the national allocation plans for ETS sectors are still in the preparation phase. For assessing the ability of Estonia, Latvia and Lithuania to reach the 20% reduction target set by the EU Climate Package, several forecasts are considered. Fig. 19 presents the actual inventory data for 1990, 2005 and 2009, and forecast data for 2015 and 2020. The forecast data are given for two scenarios: the first one is based on the emission volumes calculated by the Technical University of Athens using the PRIMES model [58]. According to the modelling results, the GHG emissions from Estonia, Latvia and Lithuania will be 20.4, 18.9 and 22.7 million tons CO₂ equivalent, correspondingly (Scenario 1). The second scenario has been developed using the national forecasts from the Report pursuant to Article 3 (2) of Decision 280/2004/EC [59–61]. Here, the 'WM' (with measures) scenario has been selected. The WM scenario assumes that the policy and measures for GHG reduction have been implemented already.

The emissions calculated for this scenario are given in Table 3. The comparison of scenarios indicates that for Estonia the scenarios are quite similar, the difference being only 0.7 million tons CO₂ equivalent. At the same time, the difference for Latvia is 2.44 and for Lithuania 4.2 million tons CO₂ equivalent.

¹ Source: National inventory.

² Source: National inventory.

³ Source: CITL.

⁴ National allocation plans decisions for the second commitment period. Or data notified by the concerned Member State and agreed on by the Commission in the NAP process.

⁵ Data notified by the concerned Member State.

⁶ Annex II, of the Effort Sharing Decision ((ECD) Decision No. 406/2009/EC).

Table 3
GHG prognoses to 2020, Mt CO₂ equiv.

Scenarios	1990	2005	2009	2015	2020	Reduction compared to 1990, %
EST 1	41.1	19.2	16.8	20.0	20.4	50
EST 2	41.1	19.2	16.8	21.1	19.7	52
LAT 1	26.6	11.4	10.7	12.2	11.8	56
LAT 2	26.6	11.4	10.7	12.8	14.2	46
LIT 1	49.6	22.6	21.6	22.9	22.7	54
LIT 2	49.6	22.6	21.6	24.7	26.9	46

Source of scenarios 1 [58]. Source of the scenario Estonia 2 [59]. Source of the scenario Latvia 2 [60]. Source of the scenario Lithuania 2 [61].

7. Conclusions

The energy sector is the main contributor to GHG emissions in Europe and the Baltic States as well. The national energy sectors in the Baltic countries differ in many aspects, particularly in terms of energy resources.

The energy sectors of the three Baltic countries were analysed from the point of energy efficiency and use of renewable energy sources. All the targets set in the EU Energy and Climate Package were evaluated in the current paper. The research was mainly focused on reaching the GHG reduction target.

Based on the GHG emission forecasts described in the article, it could be concluded that Estonia, Latvia and Lithuania can meet the targets set by the EU Climate and Energy Package for Member States. However, it would be a huge challenge for all the Baltic States.

Estonia has to find a solution for reducing the high share of oil shale in the fuel consumption. Today oil shale contributes almost 68% of GHG emissions from the energy sector.

The costs of emission reduction in Latvia are amongst the highest in the EU. Significant amount of financing is required to support the measures for emission reduction in non-ETS sector, including support to the deployment of renewable energy sources, which cannot compete with the imported fossil energy.

The main obstacles for GHG emission reduction in Lithuania are the lack of measures for GHG emission reduction. The GHG emission reduction policies in Lithuania are mainly targeted at the supply sector and oriented on the huge and expensive supply-side measures. There are no sufficient incentives to promote the use of renewables since the Lithuanian Government is committed to building a new nuclear power plant.

According to the analysed forecasts the GHG emission reduction will be much higher than the EU average targets: in Estonia for 50–52%, Latvia 46–56 and Lithuania 46–54% whilst the required EU average is 20%.

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PAPER II

Volkova, A., Roos, I., Soosaar, S., Siirde, A.

Competitiveness of wood fuel in the conditions of open electricity market in Post-Kyoto period: Case study for Estonia.

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Competitiveness of wood fuel in the conditions of open electricity market in Post-Kyoto period: case study for Estonia

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Abstract – the goal of the paper was to evaluate competitiveness of wood fuel in comparison with oil shale taking into account Estonian renewable energy support policy, open electricity market and greenhouse gas emission allowance trading mechanisms. During the research the potential for electricity capacity and electricity production where wood is used as fuel, was calculated. The electricity production costs were evaluated for two possibilities of producing electricity from wood: for wood-fired cogeneration plants and for oil shale plants with oil shale and wood co-firing process. The options of wood utilisation were compared with the reference case when the electricity is produced using only one type of fuel – the oil shale.

Index Terms – energy, energy efficiency, energy management, fuel economy.

I. INTRODUCTION

The Estonian electricity market is oriented almost to one type of fuel – oil shale. In 2009 87.4% of all electricity was produced from oil shale and the share of other fuels was modest [1]. Oil shale as a fuel is widely distributed around the world, but only Estonia uses oil shale fired power plants to supply most of its electricity to domestic customers and export power to other countries. Also, secondary fuels can be made from oil shale: shale oil and oil shale gas [2].

Estonian oil shale is a low grade (average calorific value of 8.3-8.7 MJ/kg) solid fossil fuel characterised by a high ash content (45-47%), a moderate content of moisture (11-13%) and sulphur (1.5-1.7%) having a high content of volatile matter in the combustible part (up to 90%) [3].

There is unique and long-term experience in oil shale processing and utilisation for energy purposes in Estonia. Annual electricity generation from oil shale has been in range of 7-11 TWh. The main reasons for that are: the wide availability of oil shale, its low price, sufficient number of installed mining and power capacities and developed properly functioning infrastructure in Estonia. The main positive aspect of large-scale use of oil shale is the stability of the national energy supply and the independence from electricity import.

The main disadvantages of oil shale use are the large scale environmental damage caused by oil shale mining and by fuel use in the power plants, but also the low calorific value of oil shale.

Nonetheless, in spite of these disadvantages, oil shale has remained the main fuel utilised for electricity production in Estonia.

As regards renewable electricity in Estonia, it is generated from wind and water (hydro power) as well as from biomass, including wood fuel. In 2008 the share of electricity generated from renewable sources was only 2.1% of the total electricity consumption, but due to the installation of the new wood-fired combined heat and power plants in 2009 this indicator increased up to 6.1%.

In comparison with other European Union (EU) Member States, the total electricity production is small in Estonia, but the generation of electricity per capita (6.5 MWh in 2009) is at the EU average level. In Estonia electricity production per capita is greater than in other Baltic States [4].

Use of wood for electricity generation is an essential option for increasing the renewable electricity share in Estonia. The main advantage of this fuel is that wood is a renewable resource, offering a sustainable and reliable supply. Wood is considered to be carbon neutral.

Wood fuel contains minimal amounts of sulphur and heavy metals. Also, wood is a local fuel in Estonia, and it is usually significantly cheaper than the imported fossil fuels. However, there are some disadvantages of using wood energy: the high transportation and storage costs [5].

The main factors that influence competitiveness of wood fuel, as an energy source for electricity production are Estonian renewable energy support policy, which is based on energy targets and obligations, open electricity market and greenhouse gas (GHG) emission allowance trading mechanisms. The goal of the paper is to evaluate competitiveness of wood fuel in comparison with oil shale taking all these factors into account.

II. BACKGROUND

A. Estonian energy targets and obligations

According to the EC Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market, the indicative target for Estonia is 5.1% by 2010 [6].

The EU has also adopted measures to promote combined heat and power generation, which are mainly based on the EC Directive 2004/8/EC on the promotion of cogeneration based on a useful heat demand in the internal energy market [7].

Besides, the EC Directive 2009/28/EC on the promotion of the use of energy from renewable sources, which is a part of energy and climate change legislation package, providing a framework for EU targets for greenhouse gas emission savings, has been adopted in 2009 [8].

The main targets of the above-mentioned EU directives are reflected in the National Development Plan of the Energy Sector until 2020. The Plan is based on the Sustainable Development Act and is the major strategic document directing the development of the Estonian fuel and energy sector until 2020. According to the Plan, the strategic objectives of the Estonian fuel and energy sector include increasing the share of electricity produced in cogeneration plants up to 20% of the gross consumption and increasing up to 25% the share of renewable energy sources of the final energy consumption by 2020 [9].

B. Support mechanisms for local fuels in Estonia

The utilisation of renewable energy sources is supported in Estonia using different mechanisms, such as feed-in tariffs, taxes, grant payments and some others.

As it was evaluated in previous research [5, 10], the most efficient support mechanisms for electricity produced from wood fuel have been the feed-in tariffs.

Additionally, it is planned to support the electricity produced in the new oil shale units starting from 2013, in case the CO₂ allowance price is above 10 EUR/tCO₂. Oil shale electricity will be subsidised by net capacity usage of oil shale power plants and does not depend on electricity production level. The main support mechanisms for wood and oil shale are provided in Electricity Market Act (Table I).

TABLE I
CURRENT SUBSIDY MECHANISMS FOR WOOD AND OIL SHALE
ELECTRICITY [10]

	Oil shale	Wood
Subsidy mechanism	Net capacity usage If CO ₂ quota price is above 20 EUR/tCO ₂ , then 16 EUR/MW _{el} per hour If CO ₂ quota price is 15-20 EUR/tCO ₂ , then 15 EUR/MW _{el} per hour If CO ₂ quota price is 10-14.99 EUR/tCO ₂ , then 14 EUR/MW _{el} per hour	Feed-in tariff 53.7 EUR/MW _{h,el}
Subsidy description	Subsidy is valid for oil shale plants which will start operation between January 1, 2013 and January 1, 2016. Subsidy will be valid for 20 years. The total sum of subsidy should not exceed 76.7 million EUR annually.	Electricity is produced in efficient cogeneration regime. Feed-in tariff is valid for 12 years.

C. Open electricity market

The Estonian electricity market is among the smallest in the EU and up to now has lacked effective competition

due to few alternative supply options as the market is dominated by oil shale based electricity. In Estonia, the opening of the electricity market has been slower than in most of other EU countries, where all electricity consumers are already able to choose their electricity provider as of July 2007. Estonia's electricity market has been opened gradually – since April 2010 for all consumers with annual consumption over the 2 GWh. At present, the annual consumption of all eligible customers constitutes 35% of the annual total consumption in Estonia. The full electricity market opening is planned since January 1, 2013.

Currently the Estonian electricity system works in the united synchronised system of the CIS and Baltic countries IPS/UPS and is connected through alternating current lines with Latvia and Russia. Transfer capacity of the lines from Baltic States to Russia and Belarus is relatively high. Besides, starting from April 1, 2010 Estonian electricity system is connected to one of the largest market for electrical energy in the world: Nord Pool Spot. Therefore there are good marketing opportunities for Estonian electricity suppliers.

By 2016 all Estonia's oil shale based power plants have to comply fully with the EU emission regulations. This requirement together with the market opening may trigger the wider deployment of renewable-based electricity generation in Estonia. The potential role of wood in new situation on the liberalised electricity market needs comprehensive economic analysis.

D. Post-Kyoto period in Estonia

The energy sector is the main source of GHG emissions in Estonia. In 2009, the energy sector contributed about 86% of total emissions, totalling 14.4 Tg CO₂ equivalents. Compared to the base year 1990, the emissions were about 60% below that level (36.16 Tg CO₂). Most of the energy sector emissions (97.7%) originate from fuel combustion and only 2.3% are contributed by fugitive emissions. The substantial amount of energy related emissions is caused by extensive consumption of fossil fuels for electricity and heat production. The share of oil shale, shale oil and oil shale gas combustion is about 68.5% of the energy sector total GHG emissions (Fig. 1) [11].

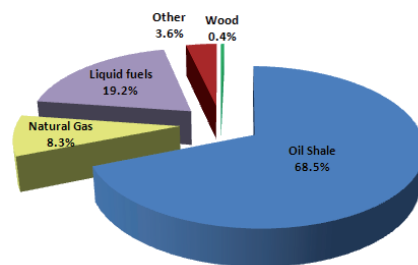


Fig. 1. GHG emissions by sources in 2008, %

The share of oil shale (including secondary fuels made from oil shale: shale oil and oil shale gas) in electricity

production is even larger totalling about 96% of the electricity production emissions in 2009 (Fig.2).

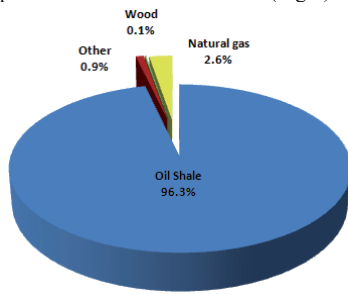


Fig. 2. GHG emissions by fuels in electricity production in 2009, %

Estonia has no problems with meeting targets set by Kyoto Protocol for 2008-2012. However, the EU has set several challenging climate and energy targets to be met by 2020. Among these there is a goal to reduce GHG emissions in the EU member states by at least 20% below the 1990 level. To promote reaching this target the European Parliament and the Council established in 2003 a scheme for GHG emission allowance trading – Emission Trading Scheme (ETS) within the Community [12].

According to the new Directive 2009/29/EC it has been decided that in the EU the full auctioning will be the rule for the power sector since 2013, as well as no free allocation will be made in respect of any electricity production by EU ETS new entrants [13]. It means that CO₂ emission level will be the factor of increasing importance for electricity production.

III. METHODOLOGY

A. Potential for electricity generation from wood

As mentioned before, during a long period the Estonian electricity market has been oriented to oil shale. Almost 95% of all electricity before 2009 has been produced from oil shale. But within the last few years the share of renewable energy resources, including the wood fuel, has increased. It is important to take into account that the potential of wood fuel for electricity production is not yet fully realised.

According to the estimation of the wood fuel resources in Estonia the potential of wood, which can be used for energy production, is 8 400 thousand m³ per year (67 200 TJ) [14]. Additionally, it is possible to use the woody biomass from the non-forest areas and the wood processing residues. In past years the consumption of wood fuel has been less than 4 000 thousand m³ per year. From the point of view of wood fuel availability there is an opportunity to double the wood fuel consumption in Estonia. But it is important that there are technological boundaries for electricity production from wood.

There are three primary technology categories used for the electricity generation from wood: direct combustion, pyrolysis and gasification [15]. At the moment direct combustion is the most appropriate technology for electricity production from wood in Estonia, which

includes two main opportunities: electricity production in wood-fired cogeneration plants and co-firing wood with oil shale in oil shale power plants.

Electricity production in wood-fired cogeneration plants is a widely used opportunity to increase the share of renewable energy sources [10, 16].

There are three wood-fired cogeneration plants operating in Estonia. In the beginning of 2009, two plants were put into operation: the Tartu Elektriijaam with capacity of 25 MW_{el} and 52 MW_{th} and the Tallinna Elektriijaam with capacity of 25.4 MW_{el} and 50 MW_{th} [5, 10]. Besides, in the beginning of 2011 a new wood-fired cogeneration plant – the Pärnu Elektriijaam with capacity of 24 MW_{el} and 50 MW_{th} was put into operation. Wood chips and peat can be used as fuel in these plants.

Back-pressure turbine technology is used in the wood-fired cogeneration plants in Estonia. The turbines expand steam down to the back-pressure, which is sufficient for producing heat at a desired temperature. The back-pressure steam turbine is reasonable when there is a continuous need for heat or steam.

Additionally there is still some potential for a new wood-fired cogeneration plant. There are few places in Estonia, where the heat load is high enough for an efficient cogeneration. For calculation of potential it was assumed that one more wood-fired cogeneration plant would be installed with electrical capacity of 25 MW_{el}.

As regards the peat share in combustion process, the technology allows to be flexible in this point. But peat is considered to be fossil fuel with relatively low calorific value and high GHG emissions. From the experience of wood-fired cogeneration plants operating in Estonia, the optimal share of peat is about 10%. By feeding the boiler partly with peat, it is possible to keep the boiler burning surfaces cleaner, thus the cogeneration plant works more efficiently.

Another possibility for electricity production from wood is co-firing wood chips with oil shale in power plants in Estonia. Indirect wood and oil shale co-firing offers a near-term solution for reducing the CO₂ emissions from the conventional fossil fuel power plants [16]. Wood co-firing is a well-proven technology which has been successfully demonstrated in more than 200 installations worldwide for most combinations of fuels and boiler types in the range 50-700 MW_{el} [18].

Two circulating fluidised bed boilers are installed in the Balti and the Eesti power plants. Both units have capacity of 215 MW_{el} and are flexible for co-firing oil shale with wood. It is possible to use up to 30% of wood chips in oil shale boilers. According to different researches and world practice the most suitable co-firing share for wood chips is 15% in fluidised bed boilers [19, 20]. In Estonia wood chips can be used as an additional fuel in the new oil shale power plant (300 MW_{el}) equipped with circulating fluidised bed technology, which will be built next to an existing Eesti power plant after 2015.

The potential for electricity capacity where wood is used as fuel can be calculated, taking into account the existing wood-fired cogeneration plants, the planned

cogeneration plants and the wood fuel resources, which can be used in oil shale power plants (1).

$$P_{wood} = \sum_{i=1}^n k_i \cdot P_{CHPi} + \sum_{j=1}^m k_j \cdot P_{CHPj} + k_{OS} \cdot P_{OS}, \quad (1)$$

$$W_{wood} = \sum_{i=1}^n k_i \cdot P_{CHPi} \cdot t_i + \sum_{j=1}^m k_j \cdot P_{CHPj} \cdot t_j + k_{OS} \cdot P_{OS} \cdot t_{OS} + k_{OS} \cdot P_{OS} \cdot t_{OS}, \quad (2)$$

where

- P_{wood} – installed capacity for electricity production from wood, MW_{el} ;
- W_{wood} – electricity produced from wood per year, GWh ;
- P_{CHPi} – installed capacity of i existing cogeneration plant, MW_{el} ;
- k_i – the share of wood used in i cogeneration plant, %;
- P_{CHPj} – installed capacity of j planned cogeneration plant, MW_{el} ;
- k_j – the share of wood used in j cogeneration plant, %;
- P_{OS} – installed capacity of oil shale units, MW_{el} ;
- k_{OS} – the share of wood used in oil shale plants, %;
- t – annual operating time, h .

The following data and assumptions were used for the calculation:

- Data about existing cogeneration plants (installed capacity, electricity production, operating time) were taken from the reports and plans of the cogeneration plants in Estonia.
- Data about existing oil shale units (installed capacity, operating time) were taken from the reports of the oil shale units in Estonia.
- Following assumptions were made concerning the planned cogeneration plant: installed capacity 25 MW_{el} , 50 MW_{th} and annual operating time 6500 h.
- Assumption both for the existing and for the planned cogeneration plants was that the share of peat is 10%.
- Concerning the new oil shale unit, the same operating time was used, as for the units already in operation.
- It was assumed that the share of wood was equal to 15% for all oil shale units.

The GHG emission can be reduced by decreasing the share of oil shale and increasing the share of wood. The emission reduction can be calculated as a difference between emissions from the oil shale combustion and the wood combustion, according to the equation (3).

$$\Delta GHG = W_{wood} (GHG_{os} - GHG_{wood}), \quad (3)$$

where

GHG_{os} – specific GHG emission factor per produced electricity unit for the oil shale fluidised bed unit, tCO_2/MWh_{el} ;

GHG_{wood} – specific GHG emission factor per produced electricity unit for the wood based electricity production, tCO_2/MWh_{el} .

The value of the carbon emission factor for the oil shale circulating fluidised bed combustion is equal to 26.94 tC/TJ (98.8 t CO_2 /TJ) [21].

A specific CO_2 emission factor per produced energy unit for the oil shale fluidised bed combustion technology is worked out by the Department of Thermal Engineering of the Tallinn University of Technology [22]. The value of the CO_2 emission factor is equal to 0.965 tons of CO_2/MWh_{el} .

During combustion of oil shale in the fluidised bed combustion boiler a small amount of N_2O is also formed. As the amount of this emission is insignificant, it was not taken into account.

According to the international agreement the CO_2 emission from wood combustion is taken equal to zero [23]. There are other GHG emissions such as CH_4 and N_2O emissions. But the amount of these emissions is negligible and it was not taken into account in further calculations.

Therefore the reduction of the GHG emissions can be calculated by the equation (4).

$$\Delta GHG = W_{wood} \cdot CO_{2os}, \quad (4)$$

where

CO_{2os} – specific CO_2 emission factor per produced electrical energy unit for oil shale fluidised bed unit, tCO_2/MWh_{el} .

B. Price comparison

To evaluate the wood fuel competitiveness in the conditions of open electricity market in Post-Kyoto period it is important to compare wood and oil shale based electricity production costs, taking into account the available subsidies and the price of CO_2 emission allowance. The calculated electricity production costs include all costs allocated to electricity production; potential profit for the producer is not included.

All calculations were made for the year 2020. This year was chosen because by that time the state support for the wood-fired cogeneration plants will be mostly stopped. The open market and the GHG emissions trading scheme will start to work earlier than 2020. Besides, the next goals according to the EU legislation to promote renewable energy are established for 2020. Estonia should produce 25% of its energy from renewable sources by 2020 [8]. Taking into account these obligations, the National Development Plan of the Energy Sector was prepared for the period until 2020.

Here the electricity production costs are evaluated for two possibilities of producing electricity from wood: for wood-fired cogeneration plants and for oil shale plants

with oil shale and wood co-firing process. For the calculation different data were collected and some assumptions were made. Concerning the first possibility to produce electricity from wood in a cogeneration plant, a reference cogeneration plant was chosen with parameters which are shown in Table II. These parameters are typical for some existing plants. As it was mentioned above, there are three plants in operation and one planned wood-fired cogeneration plant in Estonia, with rather similar parameters.

In calculations of potential electricity generation it was assumed, that the share of peat utilised in wood-fired cogeneration plants is 10%. This is the minimal share in case of wood firing, which helps to keep the boiler burning surfaces cleaner.

Regarding wood use in oil shale plants, the data for new oil shale unit were used [24] (Table II). The share of wood in primary energy was assumed as 15%.

TABLE II
PARAMETERS OF POWER PLANTS

Parameter	Wood-fired cogeneration plant	Oil shale plant
Electrical capacity, MW _{el}	25	300
Heat capacity, MW _{el}	50	–
Electrical efficiency, %	30	41
Heat efficiency, %	60	–
Total efficiency, %	90	41
Wood fuel share, %	90	20
Fossil fuel share, %	10	80

The current and the assumed future fuel prices are presented in Table III. In Estonia, according to the Electricity Market Act the price of the oil shale sold to large power plants must be regulated. At present, the Competition Authority has set a price cap of 4.54 EUR/MWh_{fuel} for the oil shale supplied to the Narva power plants. The prices of biomass, including wood chips, as well as peat are market based. Regarding fuel prices the projections are based on several sources [8; 25; 26].

TABLE III
PRICES OF FUELS (EUR/MWh_{FUEL})

Fuel	2010	2020
Oil shale	4.50	5.85
Peat (milled)	8.40	10.92
Biomass (wood chips)	14.00	20.72

In Estonia the prices of heat sold by district heating utilities are regulated by the Competition Authority. Therefore, in case of a CHP plant, the price of heat sold to district heating system is one of the key factors in calculation of price for electricity. At present, the regulated prices for wood based district heat are in the range of 40-45 EUR/MWh_{th}. Taking into account the current price structure of district heat and considering the

future projections of cost elements the price of 56 EUR/MWh_{th} was used in calculations for the year 2020.

The impact of heat and electricity production on climate change can be measured by the amount of GHG emission. In the frames of EU ETS this impact is reflected in the energy production costs as well. During ETS phases I and II the allowances for emissions were typically given free to firms. It has been decided that full auctioning of allowances shall be the rule for the power sector during the ETS phase III (since 2013), as well no free allocation shall be made in respect of any electricity production by EU ETS new entrants [13]. This means that the CO₂ emission level would be the factor of increasing importance for heat and electricity producers. In the current analysis the cost calculations were made applying the emission allowance price of 10 EUR/tCO₂. The options of wood utilisation are compared with the reference case when the electricity is produced using only one type of fuel – the oil shale.

IV. RESULTS AND DISCUSSIONS

A. Potential for electricity generation from wood and the environmental benefits

Taking into account all assumptions and data, which were mentioned above the potential of electricity produced from wood in Estonia was calculated. The results of calculation are shown in Table IV.

Using the equation (1), the total installed capacity for electricity production from wood was calculated. The total installed capacity is close to 200 MW_{el}.

According to data about the total installed electrical capacity in 2010, the wood based electricity producers could supply 6% from the overall installed capacity.

TABLE IV
POTENTIAL OF ELECTRICITY PRODUCED FROM WOOD FUEL

	Existing cogeneration plants	Planned cogeneration plants	Oil shale power plants (co-firing)	Total
Capacity (MW _{el})	66.96	22.5	109.5	198.96
Production per year (GWh)	440.28	146.25	766.5	1353.03

Using input data about operating time or planned electricity production on the assumptions which had been established, it was calculated that electricity production from wood would reach 1 350 GWh per year. It is about 13% from the average total electricity production during the last five years.

Wood fuel required for electricity production is about 2 000 TWh (7 200 TJ). This amount is equal to 10.7% of the wood potential available for electricity production in Estonia.

Using equation (4) the avoided GHG emissions were calculated. The estimated wood use for electricity production enables the reduction of the GHG emissions

by 1306 thousands CO₂ tons per year from Estonian energy sector. It is about 8% from the total greenhouse gases emissions in Estonia. Economic value of this reduction can vary from 13 to 40 million euro, according to the actual price for CO₂.

These results show that the share of electricity produced from wood fuel is significant and the woody biomass is the most important renewable energy source in Estonia.

B. Price comparison

The calculations were made taking into account the data and assumptions required for price comparison of following options:

- electricity production in wood-fired cogeneration plant, where wood is co-fired with peat;
- electricity production in oil shale unit, where oil shale is co-fired with wood;
- electricity production in oil shale unit, where only oil shale is used.

The main results of calculations are presented in Table V.

TABLE V
COMPARISON OF ELECTRICITY PRODUCTION IN POWER PLANTS

Parameter	Cogeneration plant	Oil shale plant (co-firing: oil shale and wood)	Oil shale plant (oil shale)
Electrical capacity, MW _{el}	25	300	300
Fuel mix	Wood 90% peat 10%	Oil shale 80% wood 20%	Oil shale 100%
Annual electricity production (gross), GWh	137.5	2 100.0	2 100.0
Annual heat sales, GWh	275.0	–	–
CO ₂ emission, kt	17.1	1418.4	1773.0
Electricity production costs, EUR/MWh _{el}	27.68	43.74	35.74
Price of sold heat, EUR/MWh _{th}	56.00	–	–
Production costs allocated to electricity (incl. CO ₂ cost), EUR/MWh _{el}	29.06	51.25	45.12
State subsidy, EUR/MWh _{el}	–	14.00	14.00
Production costs allocated to electricity (incl. CO ₂ cost and state subsidy), EUR/MWh _{el}	29.06	37.25	31.12

According to the results, the wood fuel can be competitive as a primary fuel for electricity generation when it is used in a cogeneration plant, even when no additional support is provided from the state.

But in case of wood usage in oil shale unit as an additional energy source it is not competitive without the state support for wood electricity. The reason is that the electricity production costs, when only oil shale is used are much lower, than in case of wood being added in the co-firing process. It can be explained by high wood fuel prices and relative cheapness of oil shale.

The basic calculations were made for the case when the price of CO₂ emission allowance is 10 EUR/tCO₂.

There are no accurate forecasts, available for the price of CO₂ emission allowance in 2020. This price can vary in a rather broad range. This factor can influence the results of calculation and this impact was evaluated by sensitivity analysis.

The sensitivity analysis for the electricity price was carried out to determine the impact of different price levels of CO₂ emission allowance. Therefore, the production costs in case of allowance prices of 10, 15, 20 and 40 EUR/t CO₂ were calculated. The results of sensitivity analysis are presented in Fig. 3.

As it can be seen from the results, the CO₂ allowance price in minor way influences the production costs allocated to electricity when the electricity is produced in

a wood-fired cogeneration plant. It can be explained by the fact that only 10% of fuel used for electricity production is fossil fuel, which emits CO₂. As a result, the electricity production costs change from 29.5 EUR/MWh to 33.2 EUR/MWh.

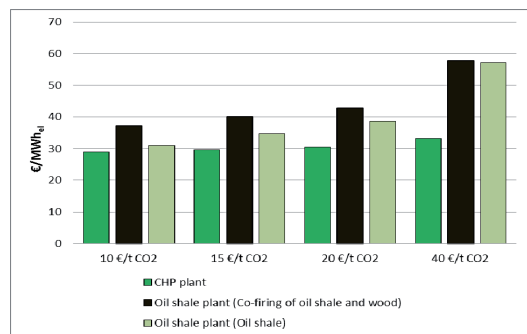


Fig. 3. Sensitivity analysis: electricity production costs depending on CO₂ allowance price

The spread between electricity production costs decreases with the CO₂ allowance price increase. It can be explained by the fact that the CO₂ allowance price impact on electricity production costs when only oil shale is used

is higher, than on electricity production costs when oil shale and wood are used in a co-firing process. If price of CO₂ allowance is 40 EUR/t CO₂, these electricity production costs become almost the same, but in all other cases oil shale and wood co-firing will not be competitive with oil shale combustion. The CO₂ allowance costs can not compensate the spread between fuel costs, because the wood fuel price is more than three times higher than the oil shale price.

For the wood-fired cogeneration plant the additional sensitivity analyses were made. As usual, there is no free market for heat sold via district heating systems and the heat price is regulated in Estonia by the Competition Authority. Therefore, the impact of heat price on the price of electricity sold by the CHP plant to the free market of electricity may be rather significant. The analysis indicated that the increase of heat price by 1 EUR/MWh_{th} enables to reduce the selling price of electricity by 1.78 EUR/MWh_{el}.

The sensitivity of allocated electricity production costs were also analysed towards the annual full load operating hours. In case the full load hours are 4 500 h/a (capacity factor 0.51) instead of 5 500 h/a (0.63) the electricity has to be sold by 41.4% higher price level. On the other hand, the 6 500 h/a (0.74) of annual full load enables to reduce the electricity price by 28.7%.

V. CONCLUSIONS

Wood fuel use for electricity production provides an essential option for increasing the renewable electricity share in Estonia. During the research the potential of electricity production from wood in Estonia was evaluated and the competitiveness of wood was analysed in comparison with the local fossil fuel oil shale for electricity production.

The potential for electricity capacity with wood used as fuel was calculated taking into account the existing wood-fired cogeneration plants, the planned cogeneration plants and the wood fuel resources, which can be used in oil shale plants by co-firing process. In result the total installed capacity for electricity production from wood is about 200 MW_{el}. These capacities could produce 1 350 GWh of electricity per year. The estimated wood use for electricity production enables the reduction of GHG emissions by 1 306 thousands CO₂ tons per year from Estonian energy sector.

This potential could be realised in case wood fuel is competitive with oil shale as primary fuel for electricity generation. To evaluate wood fuel competitiveness in conditions of open electricity market in Post-Kyoto period it is important to compare wood and oil shale based electricity production costs taking into account the available subsidies and the price of CO₂ emission allowance. Electricity production costs are evaluated for two possibilities of producing electricity from wood: for the wood-fired cogeneration plants and for the oil shale plants with oil shale and wood co-firing process. The options of wood utilisation are compared with the reference case when the electricity is produced using only

one type of fuel – the oil shale. For cost calculation the technical, economic and environmental factors were taken into account. All calculations were made for the year 2020.

In result the electricity production costs for all the cases were calculated: 29.06 EUR/MWh for wood-fired cogeneration plant (90% wood, 10% peat), 37.25 EUR/MWh for oil shale unit using co-firing (80% oil shale, 20% wood) and 31.12 EUR/MWh for reference oil shale unit (100% oil shale). According to these results, wood fuel is competitive as fuel for electricity generation in case it is used in cogeneration plants. But in case wood is used in oil shale unit as additional fuel in co-firing process with oil shale, it cannot compete with fossil fuel. It can be explained by high price of wood fuel and relative cheapness of oil shale.

The basic calculations were made for the case, when the price of CO₂ emission allowance is 10 EUR/tCO₂. The sensitivity analysis for the electricity price was made additionally to determine the impact of CO₂ emission allowance price varying in the range from 10 to 40 EUR/tCO₂. As well, the sensitivity of other factors, such as the heat price and the annual full load operating hours were analysed.

Research showed that wood fuel is not competitive as an additional fuel for electricity production in oil shale units in co-firing process without the state support. It means that there is a high risk that electricity producer will stop to use wood after the state support will be terminated. It means that in conditions of Estonia CO₂ allowance trading scheme cannot solve the task of wood fuel competitiveness as an additional fuel for electricity generation in oil shale units.

On the other hand, calculations of allocated electricity production costs in wood-fired cogeneration plants showed that in this case wood can compete with oil shale. It can be explained by high efficiency of the cogeneration plants.

There is a possibility that in case of no additional supporting measures provided to renewable electricity after 2020, the previously calculated potential for electricity production from wood in Estonia will not be realised.

One of the possible solutions for this issue could be the prolongation of support for wood as fuel for electricity generation and development of wood-fired cogeneration in Estonia.

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PAPER III

A.Siirde, I. Roos, A. Martins.

Estimation of carbon emission factors for the Estonian shale oil industry.

Oil Shale, **2011**, Vol. 28, No. 1S, pp. 127–139.

ESTIMATION OF CARBON EMISSION FACTORS FOR THE ESTONIAN SHALE OIL INDUSTRY

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In this paper the country-specific carbon emission factors for the by-products from oil shale thermal processing (generator gas, semi-coke gas and semi-coke) for different technologies are presented. Today these emission factors have still not been determined in Estonia. As the shale oil production will increase significantly in the future, major attention should be paid to the oil shale production-related emission factors.

Introduction

Estonia is the biggest shale oil producer in Europe and one of four countries in the world (Russia, Brazil and China) commercially producing shale oil. There is some use and production of shale oils also in Austria and Germany for the medicine and cosmetics industries, but the quantities there are not comparable, either with the industrial production or the use of oils.

Shale oil production has gained importance in the light of higher oil prices, declining petroleum supplies and rapidly increasing demand from emerging economies.

Shale oil refers to any synthetic oil obtained by destructive retorting of oil shale. During the extraction process, the stable organic matter embedded in oil shale is thermally cracked and converted into oil, combustible gases, solid ash and semi-coke. The composition of shale oil depends on the used extraction technique, composition of kerogen and presence of non-organic phases such as sulphur, phosphate or nitrates.

In Estonia the Kiviter-type internal combustion vertical retorts and Galoter or Solid Heat Carrier units are used for shale oil production. During

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the shale oil production, combustible by-products are formed: generator gas, semi-coke gas and semi-coke.

For oil shale retorting in the Kiviter-type retorts a certain amount of generator gas is burned to get gaseous heat carrier (hot combustion products) for oil shale retorting, while the rest of generator gas is burned in power plant boilers. Semi-coke is not burned, but stored in the oil shale waste dump. In SHC units semi-coke is burned in the aerofountain furnace to get solid heat carrier (hot ash) for oil shale retorting. The generator gas is completely burned in power plant boilers.

Shale oil production technologies

In Estonia, thermal processing of oil shale for shale oil production is carried out in three different enterprises:

- Kohtla-Järve oil plant of the *Viru Keemia Grupp AS (VKG AS)*,
- Narva oil plant (*Eesti Energia Õlitööstus AS*) and
- Kiviõli oil plant (*Kiviõli Keemiatööstuse OÜ*).

The total production of shale oil in these enterprises made about 500,000 tons in 2009 (Fig. 1).

There are two different oil shale thermal processing technologies applied in Estonia: the Kiviter-type internal combustion vertical retort [1] and the Galoter type or Solid Heat Carrier (SHC 140) unit [2]. In the present paper a brief overview of these two different oil shale processing technologies is given.

Oil shale processing in the vertical Kiviter retorts (so-called gas generators) with the gaseous heat carrier is a universal technology suitable for retorting high-calorific lump oil shale with the particle size of 25–125 mm. The vertical retort is a metal vessel lined inside with refractory bricks. The oil shale loading device (F), semi-coke unloading device (E) and extractor are arranged on the top and in the lower part of the retort vessel, respectively. Thermal processing of oil shale is carried out in the retorting chamber (C) in the cross flow of gaseous heat carrier (combustion products of generator gas). Hot gases heat up and dry oil shale, and after reaching the required temperature for retorting (450–550 °C), organic matter of oil shale starts to decompose. The mixture of heat carrier, oil and water vapour flows into the collector chamber (G) while semi-coke (retorted oil shale) moves downward to the cooling chamber (D). Oil vapours and gas are discharged from the retort to the oil separation system (H) via the outlet connections. Some of the discharged generator gas is burned in the combustion chamber of retort (A) for producing gaseous heat carrier. The most of generator gas is directed for firing into the power plant boilers. The simplified layout of oil shale retorting in vertical gas generators is given in Fig. 2.

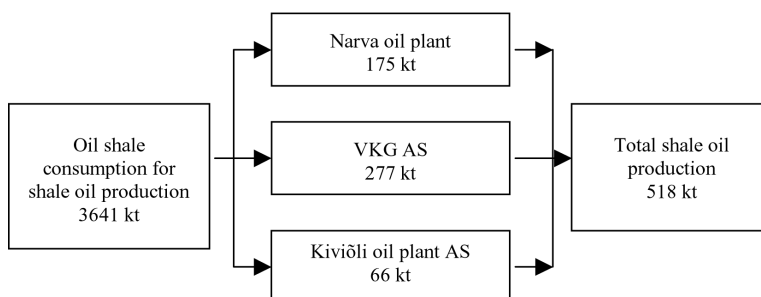


Fig. 1. Shale oil production in the Estonian oil plants in 2009, thousand tons.
Source: Oil plants data

For the oil shale retorting process with solid heat carrier (the Galoter process), the oil shale with a particle size of 0–20 mm (as received) is used. Oil shale is heated up and dried with hot flue gases from the combustion of semi-coke in the aerofountain dryer (I). Dry oil shale is mixed with hot ash (750–800 °C) – a solid heat carrier. The ash is a by-product of semi-coke combustion in the aerofountain furnace (D). The ratio of heat carrier to oil shale is regulated by the required temperature of oil vapours leaving the retort and is controlled by the position of valve arranged in the heat carrier by-pass E. Dried oil shale and hot ash (heat carrier) are mixed. The mixture of oil shale and heat carrier is fed into the horizontal rotating retort (A). Thermal treatment of oil shale starts in the mixer (K) and continues in the retort. The contact of oil shale with heat carrier results in intensive formation of shale oil vapours and semi-coke. Fine semi-coke particles are removed from the gas and oil vapours in the dust removal chamber (B) and separator (C). After shale oil being condensed from oil vapours in the oil condensation system (O), the remained semi-coke gas is directed into the power plant boilers for production of heat and power. Semi-coke leaving the retort at 460 °C is delivered to the aerofountain furnace (D) for combustion. The gases from AFC contain combustible compounds and surplus of heat in the gases makes it possible to carry out the afterburning of these gases in waste heat boiler H. Flue gases from the aerofountain dryer (I) are cleaned in the electric precipitator (L) and discharged into the atmosphere through the oil plant stack (P). A simplified layout of the solid heat carrier retorting is given in Fig. 3.

For heat generation required in oil shale processing in the described retorts different combustible by-products of oil shale oil production are used.

In order to get a gaseous heat carrier some of the generator gas is burned in the combustion chamber during oil shale retorting in the vertical retort.

Combustion products of generator gas do not emit directly from the oil plant into the atmosphere, but remain in the generator gas as its components.

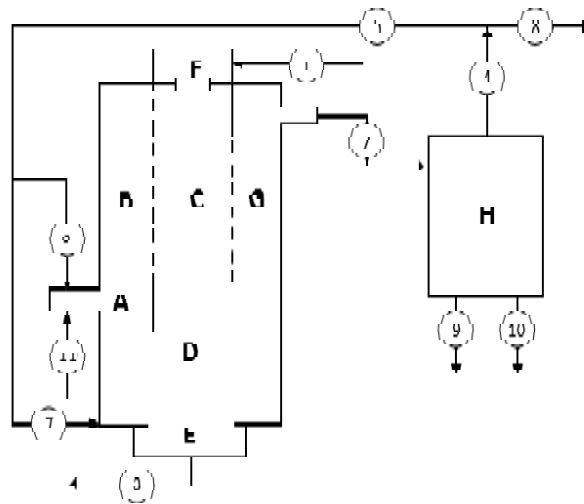


Fig. 2. Principal flow chart of oil shale retorting in the vertical retort.

Abbreviations:

A – generator gas combustion chamber; B – distribution chamber of hot gaseous combustion products (gaseous heat carrier); C – oil shale retorting chamber; D – semi-coke cooling chamber; E – semi-coke unloading device; G – collector chamber; F – oil shale loading device; H – oil separation system.

Main material flows:

1 – oil shale, 2 – oil vapours and gas; 3 – semi-coke into the oil shale waste dump; 4 – generator gas; 5 – generator gas into the retort; 6 – generator gas for burning in the retort; 7 – generator gas into the cooling chamber; 8 – generator gas for firing in the power plant boilers; 9 – shale oil to the fuel storage of oil plant; 10 – fusses; 11 – air.

Most of the generator gas is delivered to the power plants of neighbouring oil factory where it is burned for heat and power generation in the boilers. The yield of semi-coke in vertical retorts is approximately 49% per ton of raw oil shale [9]. The semi-coke which contains about 7–11.5% of carbon is not used, but stored in the dumps. In the future semi-coke will be used as a raw material in the cement industry.

Hot semi-coke ash is used for heating oil shale in the solid heat carrier retort. Hot products of semi-coke combustion are used for drying raw oil shale and after cleaning discharged into the atmosphere through the oil plant stack. Semi-coke gas is completely burned in the boilers of power plant, and its combustion products are sent into the atmosphere through the power plant stacks together with the flue gases of other fuels.

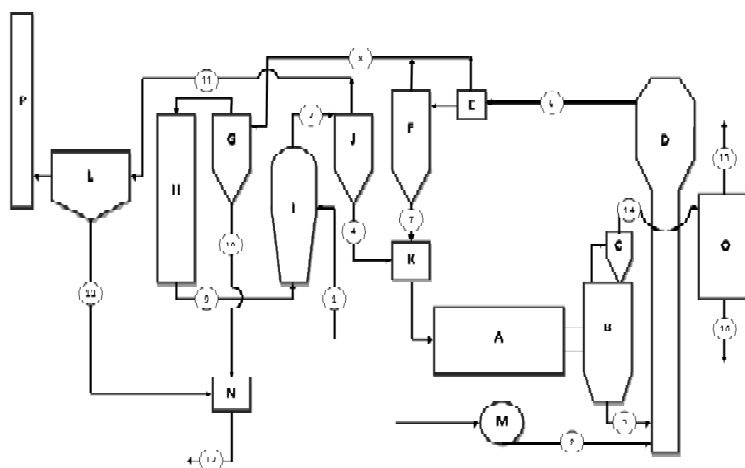


Fig. 3. Principal flow chart of retorting process with solid heat carrier.

Abbreviations:

A – reactor for oil shale pyrolysis; B – dust removal chamber; C – separator of gas and oil vapours; D – aerofountain combustor (AFC); E – by-pass; F – hot ash (heat carrier) separation cyclone; G – ash separation cyclones (1st, 2nd and 3rd stage); H – waste heat boiler; I – aerofountain dryer (AFD); J – dried oil shale separation cyclones (the 1st, 2nd and 3rd stage); K – dried oil shale and hot ash (heat carrier) mixer; L – electrostatic separator; M – centrifugal air blower; N – pulp tank; O – oil condensation system; P – stack.

Main material flows:

1 – raw oil shale, 2 – compressed air; 3 – dried oil shale with flue gases; 4 – dried oil shale; 5 – semi-coke; 6 – hot ash (solid heat carrier) with gases after semi-coke combustion in AFC; 7 – hot ash (heat carrier); 8 – mixture of ash and AFC gases after partly separated hot ash required for the oil shale pyrolysis process; 9 – flue gas; 10 – ash; 11 – flue gas to the electric precipitator; 12 – electric precipitator ash; 13 – ash pulp of the retort to the dredger unit of the power plant; 14 – oil vapours after cleaning; 15 – semi-coke gas for firing in power plant boilers; 16 – shale oil to the fuel storage of the oil factory.

Method for estimating the carbon emission factors of semi-coke gas and semi-coke for solid heat carrier technologies

During the combustion of semi-coke and semi-coke gas, carbon dioxide will be formed. For estimating the amounts of CO₂ emissions carbon emission factors for semi-coke and semi-coke gas should be worked out.

The semi-coke gas formed in the solid heat carrier is characterised with a high content of burning compounds and its approximate lower heating value is 39.8–46.8 MJ/kg [3]. Besides methane, ethane and ethene are also the

main compounds of the semi-coke gas. The composition of semi-coke gas by single compounds varies somewhat in different sources, because the composition of gas depends on the thermal processing regime. At the same time those differences are not significant.

Carbon emission factor of SHC-140 semi-coke gas

Table 1 shows the composition and heating value of semi-coke gas. The data was received from the Narva oil plant.

Table 1. Composition of semi-coke gas from the Solid Heat Carrier-140 process

Composition of semi-coke gas	Content in volume, %	Carbon mole ratio	Rate of C in gas, %	Heat value of gas Q_{scg}^r , MJ/nm ³	Rate of Q_{scg}^r , MJ/nm ³	Specific weight, kg/nm ³	Density rate, kg/nm ³
1	2	3	4=2×3	5	6=2×5/100	7	8=2×7/100
CO ₂	9.54	12/44	2.60			1.964	0.187
H ₂ S	2.53			23.384	0.592	1.52	0.038
N ₂	1.1					1.257	0.014
O ₂	0.15					1.428	0.002
CO	9.53	12/28	4.08	12.636	1.204	1.25	0.119
H ₂	13.31			10.798	1.437	0.09	0.012
CH ₄	16.80	12/16	12.60	35.820	6.018	0.72	0.12
C ₂ H ₆	10.00	24/30	8.00	63.751	6.375	1.34	0.13
C ₂ H ₄	13.01	24/28	11.15	59.066	7.684	1.25	0.16
C ₃ H ₈	4.25	36/44	3.48	91.256	3.878	1.97	0.08
C ₃ H ₆	8.23	36/42	7.05	86.005	7.078	1.88	0.15
C ₄ H ₁₀	1.29	48/58	1.07	118.651	1.531	2.59	0.03
C ₄ H ₈ +C ₄ H ₆	5.68	48/56	4.87	113.514	6.448	2.50	0.14
C ₅ H ₁₂	1.22	60/72	1.02	146.084	1.782	3.22	0.04
C ₅ H ₁₀	1.40	60/70	1.20	140.780	1.971	3.12	0.04
C ₆ H ₁₀	0.97	72/82	0.85	141.571	1.373	3.21	0.03
Total	99.01		57.97		47.37		1.318

Source: The detailed data on the composition of semi-coke gas was received from the Narva oil plant in 2009. The same data was used for preparing the Company Standard document while the data on unsaturated hydrocarbons was summarised [3, 4].

The factor of carbon emission from semi-coke gas combustion can be calculated by the following formula:

$$\begin{aligned}
 q_{c \text{ scg}} = & 10 (12/16 \cdot \text{CH}_4 + 24/30 \cdot \text{C}_2\text{H}_6 + 24/28 \cdot \text{C}_2\text{H}_4 + 36/44 \cdot \text{C}_3\text{H}_8 \\
 & + 36/42 \cdot \text{C}_3\text{H}_6 + 48/58 \cdot \text{C}_4\text{H}_{10} + 48/56 \cdot \text{C}_4\text{H}_8 + 60/72 \cdot \text{C}_5\text{H}_{12} \\
 & + 60/70 \cdot \text{C}_5\text{H}_{10} + 72/82 \text{C}_6\text{H}_{10} + 12/44 \cdot \text{CO}_2 \\
 & + 12/28 \cdot \text{CO})/Q_{\text{scg}}^r, \text{ tC/TJ},
 \end{aligned} \tag{1}$$

where

$q_{c \text{ scg}}$ – carbon emission factor of semi-coke gas, tC/TJ;

C_{Σ} – total carbon content in semi-coke gas, % and

Q_{scg}^r – lower heating value of semi-coke gas, MJ/kg.

Calculations:

Q_{scg}^r – lower heating value of semi-coke gas = 47.37 MJ/ nm³;

ρ_{scg} – density of semi-coke gas 1.318 kg/nm³ and

$Q_{\text{scg}}^r = Q_{\text{sg}}^r / \rho_{\text{sg}} = 47.37/1.318 = 35.94 \text{ MJ/kg}$.

The carbon emission factor of semi-coke gas:

$$q_{c \text{ scg}} = 10 \cdot C_{\Sigma} / Q_{\text{scg}}^r = 10 \cdot 57.97 / 35.94 = 16.13 \text{ tC/TJ}.$$

Carbon emission factor of SHC-140 semi-coke

For the production of shale oil in a SHC unit, raw oil shale with the average lower heating value $Q_{\text{os}}^r = 8.34 \text{ MJ/TJ}^*$ is used.

Since the average organic content of the solid heat carrier (semi-coke and oil shale dust) leaving the retort is 3.79% (C = 3.69% and H = 0.1%) and the ratio of semi-coke to ash equals 1/1.878, the carbon content of semi-coke could be calculated: $(1+1.878) \cdot 3.69 = 10.62\%$ [4].

For calculating the carbon emission factor of semi-coke, heating value of oil shale (not of semi-coke) is used, and that allows calculating CO₂ emissions from the combustion of semi-coke based on the used oil shale. Due to a smaller extent of carbonate decomposition, the improved lower heating value of oil shale can be calculated (see Formula 4) [5]. The decomposition rate of the carbonate part of semi-coke in the aerofountain furnace is calculated as follows:

$$k_C = 0.47 \cdot \text{CO}_{2\text{scg}} / (\text{CO}_2)_{\text{os}}^r, \tag{2}$$

where

k_C – decomposition rate of of semi-coke;

0.47 – ratio of semi-coke gas to gas-vapour mixture [6];

$\text{CO}_{2\text{scg}}$ – content of CO₂ in semi-coke gas, % (see Table 1) and

$(\text{CO}_2)_{\text{os}}^r$ – content of CO₂ in oil shale as received, % [7].

$$k_C = 0.47 \cdot 9.54 / 20.1 = 0.223$$

* Eesti Energia AS data

The carbon emission factor of semi-coke is calculated using the following formula:

$$q_{c\ sc} = 10 \cdot [C_{sc}^r + k_c \cdot (CO_2)_M^r \cdot 12/44] / Q_{os}^r, \text{ tC/TJ}, \quad (3)$$

where

- $q_{c\ sc}$ – carbon emission factor of semi-coke;
- C_{sc}^r – carbon content of semi-coke, %;
- $(CO_2)_M^r$ – content of mineral CO_2 in oil shale, %;
- k_c – decomposition rate of the carbonate part of semi-coke in the aerofountain furnace;
- Q_{os}^r – improved heating value of oil shale, MJ/kg.

$$Q_{os}^r = Q_{os}^r + \Delta Q \quad (4)$$

where

- Q_{os}^r – lower heating value of oil shale, MJ/kg and
- ΔQ – heat effect caused by non-decomposition of carbonates, MJ/kg [9].

$$\Delta Q = 0.0406 (1 - k_c) (CO_2)_M^r, \quad (5)$$

$$\Delta Q = 0.0406 \cdot (1 - 0.223) \cdot 17.6 = 0.5552$$

$$Q_{os}^r = 8.34 + 0.5552 = 8.895 \text{ MJ/kg}$$

$$q_{c\ sc} = 10 \cdot [10.62 + 0.223 \cdot 17.6 \cdot 12/44] / 8.895 = 13.14 \text{ tC/TJ}$$

The combustion of semi-coke in the aerofountain furnace is performed under the conditions of air shortage ($\alpha < 1$). Therefore the value of oxidation factor (k_{ox}) by the combustion of semi-coke is approximately 0.7. CO_2 emission factor of semi-coke can be calculated as follows:

$$q_{CO_2\ sc} = q_{c\ sc} \cdot k_{ox} \cdot 44/12 \text{ tCO}_2/\text{TJ}, \quad (6)$$

where

- $q_{CO_2\ sc}$ – CO_2 emission factor of semi-coke;
- k_{ox} – oxidation factor of semi-coke.

$$q_{CO_2\ sc} = 13.14 \cdot 0.7 \cdot 44/12 = 33.73 \text{ tCO}_2/\text{TJ}.$$

During oil shale retorting in the SHC-140, carbon dioxide will be formed at semi-coke combustion in the aerofountain furnace. The amount of CO_2 can be calculated by multiplying the amount of processed raw oil shale (measured in terajoules) with the carbon dioxide emission factor.

Estimation of the carbon emission factor for generator gas formed as a by-product of shale oil production in the Kiviter-type vertical retorts

The carbon emission factor of the VKG oil plant generator gas:

In Table 2 the composition of generator gas from the VKG oil plant is presented. Based on the composition the heating value and specific weight of the generator gas were calculated.

Table 2. Composition of the generator gas from the Kiviter type vertical retort (in the VKG oil plant) [8]

Com- position of generator gas	Content in volume, %	Carbon mole ratio	Rate of C in gas, %	Heat value of gas Q_{gg}^r , MJ/nm ³	Rate of Q_{gg}^r , MJ/nm ³	Rate of Q_{gg}^r , kcal/nm ³	Specific weight, kg/nm ³	Density rate kg/nm ³
1	2	3	4=2×3	5	6=2×5/100	6=2×5/100	7	8=2×7/100
CO ₂	17.3	12/44	4.72				1.964	0.3398
H ₂ S	0.4			23.384	0.094	22.34	1.52	0.0061
N ₂	65.8						1.257	0.8271
O ₂	1.1						1.428	0.0157
CO	7.3	12/28	3.13	12.636	0.922	220.31	1.25	0.0913
H ₂	5.4			10.798	0.583	139.27	0.09	0.0049
CmHn ¹⁾	2.7	24/28	2.31	71.179	1.922	459.00	1.251	0.0338
Total Σ	100.00		10.16		3.52	840.92		1.3186

¹⁾ When the content of unsaturated hydrocarbons in the gas remains below 3%, the sum of these gases is equalled to ethene (C₂H₄) with lower heating value of 71.179 MJ/nm³ [9].

The carbon emission factor for the generator gas can be calculated by using the formula (1).

$$q_{c\ gg} = 10 \cdot C_{\Sigma} / Q_{gg}^r \text{ tC/TJ}, \quad (7)$$

where

$q_{c\ gg}$ – carbon emission factor of generator gas, tC/TJ;

C_{Σ} – total carbon content in generator gas, % and

Q_{gg}^r – lower heating value of generator gas, MJ/kg.

Calculations:

Q_{gg}^r – lower heating value of generator gas: 3.52 MJ/nm³;

ρ_{gg} – density of generator gas: 1.3186 kg/nm³ and

$Q_{gg}^r = Q_{gg}^r / \rho_{gg} = 3.52/1.3186 = 2.67$ MJ/kg (without heating value of benzene gas).

Carbon emission factor of generator gas (VKG oil factory):

$$q_{c\ gg} = 10 \cdot 10.16 / 2.67 = 38.06 \text{ tC/TJ}.$$

Carbon emission factor of Kiviõli oil plant generator gas

In Table 3 the composition of generator gas from the Kiviõli oil plant is presented.

Table 3. Composition of the generator gas from the Kiviter type vertical retort in Kiviõli [10]

Composition of generator gas	Content in volume, %	Carbon mole ratio	Rate of C in gas, %	Heat value of gas Q_{Σ}^r , MJ/nm ³	Rate of Q^r , MJ/nm ³	Rate of Q^r , kcal/nm ³	Specific weight, kg/nm ³	Density rate, kg/nm ³
1	2	3	4=2×3	5	6=2×5/100	6=2×5/100	7	8=2×7/100
CO ₂	17.2	12/44	4.69				1.964	0.3378
H ₂ S	0.3			23.384	0.070	16.76	1.52	0.0046
N ₂	67.0						1.257	0.8422
O ₂	0.8						1.428	0.0114
CO	3.5	12/28	1.50	12.636	0.442	105.63	1.25	0.0438
H ₂	7.0			10.798	0.756	180.53	0.09	0.0063
CmHn ¹⁾	1.8	24/28	1.54	71.179	1.281	306.0	1.251	0.0225
Total Σ	97.6		7.73		2.55	608.92		1.2686

¹⁾ When the content of unsaturated hydrocarbons in the gas remains below 3%, the sum of these gases is equalled to ethene (C₂H₄) with lower heating value of 17,000 kcal/nm³ [9].

The carbon emission factor for the generator gas can be calculated with using the formula (1).

$$q_{c\text{ gg}} = 10 \cdot C_{\Sigma} / Q_{\text{gg}}^r \text{ tC/TJ}, \quad (8)$$

where

$q_{c\text{ gg}}$ – carbon emission factor of generator gas, tC/TJ;

C_{Σ} – total carbon content in generator gas, % and

Q_{gg}^r – lower heating value of generator gas, MJ/kg.

Calculations:

Q_{gg}^r – lower heating value of generator gas: 2.55 MJ/nm³;

ρ_{gg} – density of generator gas: 1.2686 kg/nm³ and

$Q_{\text{gg}}^r = Q_{\text{gg}}^r / \rho_{\text{gg}} = 2.55/1.2686 = 2.01$ MJ/kg (without heating value of benzene gas).

Carbon emission factor of generator gas (in Kiviõli):

$$q_{c\text{ gg}} = 10 \cdot 7.73 / 2.01 = 38.46 \text{ tC/TJ}.$$

Corrected carbon emission factors of generator gas

The generator gas contains benzene gas gases: in the VKG oil plant $b = 16\text{--}24$ g/nm³ (mean ~ 20 g/nm³) [8] and in the Kiviõli oil plant $b = 8\text{--}40$ g/nm³, (mean 24 g/nm³) [10]. If to take into consideration the benzene

gas content of generator gases, the corrected carbon emission factor for the generator gas can be calculated as

$$q_{c\ ggb} = q_{c\ gg} \cdot Q_{gg}^r / (Q_{gg}^r + b \cdot Q_{gb}^r) + q_{c\ gb} \cdot b \cdot Q_{gb}^r / (Q_{gg}^r + b \cdot Q_{gb}^r), \text{ tC/TJ}, \quad (9)$$

where

- $q_{c\ ggb}$ – carbon emission factor of generator gas with benzene gas, tC/TJ;
- $q_{c\ gb}$ – carbon emission factor of benzene gas, tC/TJ;
- Q_{gb}^r – heating value of benzene gas, MJ/kg and
- b – benzene gas content of generator gas, kg/nm³.

Table 4. Corrected carbon emission factors of generator gas

	VKG oil plant	Kiviõli oil plant
Carbon emission factor of generator gas, tC/TJ	38.06	38.46
Carbon emission factor of benzene gas, tC/TJ [11]	19.91	19.91
Heating value of generator gas, MJ/ nm ³	3.52	2.55
Heating value of benzene gas, MJ/kg [11]	44.0	44.0
Medium benzene gas content of generator gas, kg/nm ³	0.02	0.024
Corrected carbon emission factor (generator gas with benzene gas), tC/TJ	34.43	33.03

Carbon stored in semi-coke

Semi-coke removed from vertical retorts contains a small amount of organic matter that can be fired. Up to now, semi-coke has not been used but stored in the shale waste dump near the oil plants. The carbon content factor of semi-coke for calculating the carbon amount stored in semi-coke can be found by the following formula:

$$q_{c\ sc} = 10 \cdot C_{sc}^d / Q_{sc}^r \text{ tC/TJ}, \quad (10)$$

where

- C_{sc}^d – carbon content of semi-coke, %;
- Q_{sc}^r – heating value of semi-coke, MJ/kg.

The carbon content factor of semi-coke for calculating the carbon amount stored in semi-coke from the VKG AS ($C_{sc}^d = 11.3\%$; $Q_{sc}^r = 4.0$ MJ/kg) is:

$$q_{c\ sc} = 10 \cdot 11.3 / 4.0 = 28.25 \text{ tC/TJ}.$$

Conclusions

In the present paper the carbon emission factors of by-products from oil shale thermal processing and calculation methods for the emission factors are presented for the first time. The results are given in Table 5.

The carbon content factor of semi-coke can be found by the formula (10) and used for calculating the stored carbon amount in semi-coke.

Table 5. Carbon emission factors of by-products from oil shale thermal processing

Technology	By-product	Carbon emission factor, tC/TJ	
Narva oil plant			
SHC-140 process	Semi-coke gas	$q_{c\ scg}$	16.13
SHC 140 process	Semi-coke	$q_{c\ sc}$	13.14 ¹⁾
VKG oil plant			
Kiviter-type vertical retorts	Generator gas	$q_{c\ gg}$	34.43
Kiviõli oil plant			
Kiviter-type vertical retorts	Generator gas	$q_{c\ gg}$	33.03

¹⁾ The amount of carbon in semi-coke combustion products can be calculated by multiplying the amount of used raw oil shale (in terajoules) with the carbon emission factor $q_{c\ sc}$.

In this paper the carbon emission factors of by-products from oil shale thermal processing are calculated basing on available data. If the composition of generator gas, semi-coke gas or semi-coke will be specified, the proposed calculation method of carbon emission factors for these fuels could be used.

The results of the paper will be used in the annual Estonian National Greenhouse Gas Inventories for reporting to the European Commission and UNFCCC Secretariat according to the Estonia's Commitment under the Kyoto Protocol.

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3. Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinn University of Technology	2004 –	Mechanical and instrumental engineering, PhD student
Tallinn Polytechnical Institute (Tallinn University of Technology)	1981	Thermal Power Engineering, Dipl. eng. on thermal power engineering (equal to master degree)
Tallinn School of Economics	1976	High school education

4. Language competence/skills (fluent; average, basic skills)

Language	Level
Estonian	fluent
English	good
Russian	good
German	average
Finnish	basic skills

5. Special Courses

Period	Educational or other organisation
2012	Special Training on: Assessment of a GHG verifier, Estonian Accreditation Centre.
2009	Special Training on Greenhouse Gas inventory software <i>Reporter, UNIPCC Secretariat in Bonn</i>
2008	Special Training on the implications of the IPCC 2006 Guidelines for national GHG inventories. European Environmental Agency, in Copenhagen.
2007	Special Training on Climate Change and Climate Policy in Finnish Ministry of Environment and Institute of Meteorology
2000	Training in Environmental Energy Management – TEEM (EU Synergy programme) at the Ministry of Economic Affairs of the republic of Estonia
1995	<i>U.S. Country Studies Program Greenhouse Gas Mitigation Assessment, Lawrence Berkeley Laboratory, California, USA</i>

6. Professional Employment

Period	Organisation	Position
2003 –	Tallinn University of Technology, Department of Thermal Engineering	Researcher
1981–2003	Estonian Energy Research Institute at Tallinn Technical University	Researcher
2001–2002	Estonian Energy Research Institute, Laboratory of Energy Economy and Planning	Researcher
1982–1991	Institute of Thermo- and Electrophysics of Estonian Academy of Sciences	Junior researcher
1981–1982	Institute of Thermo- and Electrophysics of Estonian Academy of Sciences of Estonia	Engineer
1981–1981	Computing Centre of the Ministry of Procurements and Reserves	Programmer

7. Scientific work

Natural Sciences and Engineering, Energy Research

8. Defended theses

Comparison of heat supply options in the Ranna Poultry Farms, diploma thesis, TPI, 1981

9. Main areas of scientific work/Current research topics

Natural sciences and engineering, power engineering and environmental research

10. Other recent research projects:

1. Greenhouse Gas Emissions in Estonia 1990–2010. National Inventory Report under the UNFCCC and the Kyoto Protocol, Tallinn, 2012. Energy Sector (2012).
2. INTERREG IV B project „The Baltic Sea Bioenergy Promotion Program (Bioenergy Promotion)“ (2009–2012).
3. Greenhouse Gas Emissions in Estonia 1990–2009. National Inventory Report under the UNFCCC and the Kyoto Protocol, Tallinn, 2011. Energy Sector (2011).
4. Greenhouse Gas Emissions in Estonia 1990–2008. National Inventory Report under the UNFCCC and the Kyoto Protocol, Tallinn, 2010. Energy Sector (2010).
5. Greenhouse Gas Emissions in Estonia 1990–2007. National Inventory Report under the UNFCCC and the Kyoto Protocol, Tallinn, 2009. Energy Sector (2009).
6. Greenhouse Gas Emissions in Estonia 1990–2006. National Inventory Report under the UNFCCC and the Kyoto Protocol, Tallinn, 2008. Energy Sector (2008).
7. EU VI framework program „Bioenergy in Motion“ (Bioenergy for Heating and Cooling) (2007–2008).

ELULOOKIRJELDUS

1. Isikuandmed

Ees- ja perekonnanimi	Inge Roos
Sünniaeg ja -koht	18.12.1956, Ambla
Kodakondsus	Eesti

2. Kontaktandmed

Address	Ehitajate tee 5, 19086 Tallinn, Eesti
Telefon	+372 662 1612
E-posti address	inge.roos@ttu.ee

3. Hariduskäik

Õppeasutus	Lõpetamise aeg	Haridus
Tallinna Tehnikaülikool	2004 –	Masina ja aparaadiehitus, doktoriõpe
Tallinna Polütehniline Instituut	1981	Soojusenergeetika, Dipl. soojustehnika insener (võrdsustatud tehnika-teaduste magistrikraadiga)
Tallinna Majandustehnikum	1976	Kesk-eriharidus, programmeerimistehnik

4. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Eesti keel	kõrgtase (emakeel)
Inglise keel	kesktase
Vene keel	kesktase
Saksa keel	kesktase
Soome	algtase

5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
2011	Eesti Akrediteerimiskeskuse koolitus kasvuhoonegaaside heitkoguste tõendajate assessoritele, Tallinnas.
2008	Koolitus teemal: IPCC 2006. aasta juhendmaterjalide kasutamisest riikliku kasvuhoonegaaside inventuuri läbiviimisel. Euroopa Keskkonnaagentuur, Kopenhaagenis.
2009	Kasvuhoonegaaside riikliku inventuuri esitamise tarkvara „Reporter” alane koolitus, ÜRO Kliimasekretariaat Bonnisis.
2007	Koolitus teemal: Kliimamuutused ja kliimapoliitika, Soome Keskkonnaministeerium ja Meteoroloogia Instituut, Helsingis.
2000	Koolitus teemal: Keskkonnateadlik energiamajandus, Majandusministeerium, EU Synergy programmi <i>Environmental Energy Management – TEEM</i> raames.
1995	Täienduskursus <i>U.S. Country Studies Program</i> raames teemal: <i>Kasvuhoonegaaside mõju leevendamise võimaluste uurimine</i> , Lawrence Berkeley nimeline Teadusuuringute Laboratoorium, California, USA.

6. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2003–	Tallinna Tehnikaülikool, Soojus- tehnika Instituut, Soojusjõuseadmete õppetool	teadur
2003–2004	TTÜ Eesti Energeetika Instituut Energiamajanduse laboratoorium	teadur
1995–1995	Country Studies Management Team (CSMT), USA, Washington D.C.	külalisteadur
1991–2002	Eesti Energeetika Instituudi	teadur

Töötamise aeg	Tööandja nimetus	Ametikoht
	Energiamajanduse laboratoorium	
1982–1991	ENSV TA Termofüüsika ja Elektrofüüsika Instituudi üldenergeetika sektor	nooremteadur
1981–1982	ENSV TA Termofüüsika ja Elektrofüüsika Instituudi üldenergeetika sektor	insener
1981–1981	ENSV Varumisministeeriumi arvutuskeskus	programmeerija

7. Teadustegevus

Loodusteadused ja tehnika, energeetika- ja keskkonnaalased uuringud.

11. Kaitstud lõputööd

Ranna linnufarmide soojusvarustuse variantide võrdlus, diplomitöö, TPI, 1981.

8. Teadustöö põhisuunad

Energeetika- ja keskkonnaalased alased uuringud

9. Teised uurimisprojektid (viimasel 5 aastal)

1. Energeetika valdkonna Eesti riikliku kasvuhoonegaaside 1990–2010 aasta inventuuri ja inventuuri aruande koostamine (2012).
2. Interreg IVB Programm, Bioenergia kasutamise edendamine Balti mere äärsetes riikides (Bioenergy promotion) (2009–2012).
3. Energeetika valdkonna Eesti riikliku kasvuhoonegaaside 1990–2009 aasta inventuuri ja inventuuri aruande koostamine (2011).
4. Energeetika valdkonna Eesti riikliku kasvuhoonegaaside 1990–2008 aasta inventuuri ja inventuuri aruande koostamine (2010).
5. Energeetika valdkonna Eesti riikliku kasvuhoonegaaside 1990–2007 aasta inventuuri ja inventuuri aruande koostamine (2009).
6. Energeetika valdkonna Eesti riikliku kasvuhoonegaaside 1990–2006 aasta inventuuri ja inventuuri aruande koostamine (2008).
7. EL VI raamprogramm, Uusi innovatiivseid bioenergia tehnoloogiaid tutvustav film (2007–2008).

**DISSERTATIONS DEFENDED AT
TALLINN UNIVERSITY OF TECHNOLOGY ON
MECHANICAL ENGINEERING**

1. **Jakob Kübarsepp**. Steel-Bonded Hardmetals. 1992.
2. **Jakub Kõo**. Determination of Residual Stresses in Coatings & Coated Parts. 1994.
3. **Mart Tamre**. Tribocharacteristics of Journal Bearings Unlocated Axis. 1995.
4. **Paul Kallas**. Abrasive Erosion of Powder Materials. 1996.
5. **Jüri Pirso**. Titanium and Chromium Carbide Based Cermets. 1996.
6. **Heinrich Reshetnyak**. Hard Metals Serviceability in Sheet Metal Forming Operations. 1996.
7. **Arvi Kruusing**. Magnetic Microdevices and Their Fabrication methods. 1997.
8. **Roberto Carmona Davila**. Some Contributions to the Quality Control in Motor Car Industry. 1999.
9. **Harri Annuka**. Characterization and Application of TiC-Based Iron Alloys Bonded Cermets. 1999.
10. **Irina Hussainova**. Investigation of Particle-Wall Collision and Erosion Prediction. 1999.
11. **Edi Kulderknup**. Reliability and Uncertainty of Quality Measurement. 2000.
12. **Vitali Podgurski**. Laser Ablation and Thermal Evaporation of Thin Films and Structures. 2001.
13. **Igor Penkov**. Strength Investigation of Threaded Joints Under Static and Dynamic Loading. 2001.
14. **Martin Eerme**. Structural Modelling of Engineering Products and Realisation of Computer-Based Environment for Product Development. 2001.
15. **Toivo Tähemaa**. Assurance of Synergy and Competitive Dependability at Non-Safety-Critical Mechatronics Systems design. 2002.
16. **Jüri Resev**. Virtual Differential as Torque Distribution Control Unit in Automotive Propulsion Systems. 2002.
17. **Toomas Pihl**. Powder Coatings for Abrasive Wear. 2002.
18. **Sergei Letunoviš**. Tribology of Fine-Grained Cermets. 2003.
19. **Tatyana Karaulova**. Development of the Modelling Tool for the Analysis of the Production Process and its Entities for the SME. 2004.
20. **Grigori Nekrassov**. Development of an Intelligent Integrated Environment for Computer. 2004.
21. **Sergei Zimakov**. Novel Wear Resistant WC-Based Thermal Sprayed Coatings. 2004.
22. **Irina Preis**. Fatigue Performance and Mechanical Reliability of Cemented Carbides. 2004.
23. **Medhat Hussainov**. Effect of Solid Particles on Turbulence of Gas in Two-Phase Flows. 2005.
24. **Frid Kaljas**. Synergy-Based Approach to Design of the Interdisciplinary Systems. 2005.

25. **Dmitri Neshumayev.** Experimental and Numerical Investigation of Combined Heat Transfer Enhancement Technique in Gas-Heated Channels. 2005.
26. **Renno Veinthal.** Characterization and Modelling of Erosion Wear of Powder Composite Materials and Coatings. 2005.
27. **Sergei Tisler.** Deposition of Solid Particles from Aerosol Flow in Laminar Flat-Plate Boundary Layer. 2006.
28. **Tauno Otto.** Models for Monitoring of Technological Processes and Production Systems. 2006.
29. **Maksim Antonov.** Assessment of Cermets Performance in Aggressive Media. 2006.
30. **Tatjana Barashkova.** Research of the Effect of Correlation at the Measurement of Alternating Voltage. 2006.
31. **Jaan Kers.** Recycling of Composite Plastics. 2006.
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33. **Hans Rämmal.** Experimental Methods for Sound Propagation Studies in Automotive Duct Systems. 2007.
34. **Meelis Pohlak.** Rapid Prototyping of Sheet Metal Components with Incremental Sheet Forming Technology. 2007.
35. **Priidu Peetsalu.** Microstructural Aspects of Thermal Sprayed WC-Co Coatings and Ni-Cr Coated Steels. 2007.
36. **Lauri Kollo.** Sinter/HIP Technology of TiC-Based Cermets. 2007.
37. **Andrei Dedov.** Assessment of Metal Condition and Remaining Life of In-service Power Plant Components Operating at High Temperature. 2007.
38. **Fjodor Sergejev.** Investigation of the Fatigue Mechanics Aspects of PM Hardmetals and Cermets. 2007.
39. **Eduard Ševtšenko.** Intelligent Decision Support System for the Network of Collaborative SME-s. 2007.
40. **Rünno Lumiste.** Networks and Innovation in Machinery and Electronics Industry and Enterprises (Estonian Case Studies). 2008.
41. **Kristo Karjust.** Integrated Product Development and Production Technology of Large Composite Plastic Products. 2008.
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48. **Kristjan Juhani.** Reactive Sintered Chromium and Titanium Carbide-Based Cermets. 2009.
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50. **Igor Krupenski**. Numerical Simulation of Two-Phase Turbulent Flows in Ash Circulating Fluidized Bed. 2010.
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55. **Tõnu Roosaar**. Wear Performance of WC- and TiC-Based Ceramic-Metallic Composites. 2010.
56. **Alina Sivitski**. Sliding Wear of PVD Hard Coatings: Fatigue and Measurement Aspects. 2010.
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59. **Jürgen Riim**. Calibration Methods of Coating Thickness Standards. 2011.
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