THESIS ON NATURAL AND EXACT SCIENCES B135

Application and Elaboration of Accounting Approaches for Sustainable Development

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Dissertation was accepted for the defence of the degree of Doctor of Philosophy in Chemistry on June 20, 2012

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Defence of the thesis: October 26, 2012

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.

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ISSN 1406-4723
ISBN 978-9949-23-345-8 (publication)
ISBN 978-9949-23-346-5 (PDF)

LOODUS- JA TÄPPISTEADUSED B135

Jätkusuutliku arengu arvestusmeetodite arendamine ja rakendamine

OLGA GAVRILOVA

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CONTENTS

ABBREVIATIONS

CBA	Cost-Benefit Analysis
CHP	Combined Heat and Power Plant
DMI	Domestic Material Input
EE Ltd.	Eesti Energia Limited
EEA	Eco-Efficiency Analysis
EEBT	Emission Embodied in Bilateral Trade
EF	Ecological Footprint
EIA	Environmental Impact Assessment
EEIO	Environmentally Extended Input-Output Analysis
EP Ltd.	Eesti Põlevkivi Limited
EU27	European Union
Eurostat	European Statistical Office
FAO	Food and Agriculture Organisation of the United Nations
FCA	Full Carbon Accounting
GWB	Groundwater Body
IOA	Input-Output Analysis
IO table	Input-Output table
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LULUCF	Land Use and Land Use Change
MCDA	Multi-Criteria Decision Analysis
MFA	Material Flow Analysis
MRIO	Multi-Regional Input-Output analysis
OECD	Organisation for Economic Co-operation and Development
PIOA	Physical Input-Output Analysis
PP	Power Plant
SA	Sustainability Assessment
SD	Sustainable Development
SEEA	System of Environmental-Economic Accounts
SLCA	Social Life Cycle Assessment
TPES	Total Primary Energy Supply
UN	United Nations
UNEP	UN Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WFD	Water Framework Directive
WSSD	World Summit on Sustainable Development

Chemical formulas

CH_4	methane
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
GHG	greenhouse gases
H_2S	hydrogen sulphide
K	potassium
N	nitrogen
N_2O	nitrous oxide
NO_x	nitrogen oxides
P	phosphorus
PAHs	polycyclic aromatic hydrocarbons
SO_2	sulphur dioxide
SO_4	sulphate
VOCs	volatile organic compounds

Units

GJ	gigajoule
TJ	terajoule
ha	hectare
km^2	square kilometre
ktC/yr	thousand tonnes of carbon per year
kha	thousand hectares
m^2	square meter
m^3	cubic meter
t	tonne

1. INTRODUCTION

1.1. Background

Stressful environmental disasters and calamities, following intensive human economic activities and pressures on the environment in the fifties and the sixties of the last century forced global society to act towards reduction of these pressures and to articulate a way forward to economically beneficial and environmentally friendly development. The efforts were arranged in the elaboration of a concept – sustainable development (SD). The concept stipulated trade-offs and synergy among the main needs and aims of human society: economic, environmental and social dimensions [112]. Nowadays, the concept has become an inherent part of the national policies of many countries around the world.

An accounting system, consisting of accounting approaches and sets of indicators, has been developed to assess and understand how the main dimensions of society are interrelated and affect each other, and to monitor and manage changes taken place in the framework of processes whose eventual aim is SD. The accounting system focuses on interactions that have occurred on different levels of economic activities: product and industry-oriented, regional and national. Each accounting approach is considered to be an advanced and solid tool, which allows for completing accurate and transparent analysis. However, in spite of a long evaluation practice, the approaches still have several disadvantages (methodological limitations, uncertainties), which can affect the accuracy, reliability and quality of the results needed to make final decisions regarding the interactions under product manufacturing or sector operation towards SD. These limitations are also becoming more critical and claiming more attention in the determination of the overall environmental pressure associated with the economic activity of a country as well as in the development process of global environmental policy in the era of a rapidly interconnecting and globalising world. Since, globalisation not only "interconnects" countries, as a result of the exchange and movement of people, information and products, but also "breaks down" the boundaries of countries through trade liberalisation and the emergence of a worldwide common market. The latter in the conditions of different country-specific environmental standards and levels of economic development could make it possible for a country or sector as a producer to "escape responsibility" for environmental pressure through shifting the manufacturing processes (or a chain of processes) of "dirty" products to countries where environmental requirements are not so high and rigorous and production costs are much lower, and import the produced products essentially without their emissions "embodied" in their own economies. Hence, there are needs for well-elaborated, solid, advanced and detailed accounting approaches, which take into account the overall environmental pressure associated with a product uniformly in the interests of the global community, and assigning the responsibility for the pressures to the beneficiaries – as well as consumers, not just producers.

The focus of the dissertation was placed on three approaches of the SD accounting system: life cycle assessment (LCA), environmentally extended input-output analysis (EEIO) and full carbon accounting (FCA). The advantages and disadvantages (limitations) of the approaches were addressed and analysed. The analysis was performed in the framework of the three case studies, which allowed: (1) the interactions between the oil shale-based Estonian energy sector and the environment to be analysed and understood using the extended LCA; (2) Estonia's contribution to greenhouse gas (GHG) global emissions to be examined taking into account GHG emissions associated with Estonia's bilateral trade using the EEIO; and (3) the interactions between the consumption of feed products in Austria's husbandry sector and the emissions resulting from changes in land use in Brazil and Argentina to be investigated using the FCA.

The dissertation is structured as follows: Section 2 discusses the concept of SD and focuses on the SD accounting approaches that were employed in the case studies (i.e. LCA, EEIO and FCA). Section 3 presents the results of the studies of the interactions between the economic activities and environment in the framework of the three case studies. Section 4 presents a summary of the main results obtained and conclusions made regarding environmental pressures due to production and consumption of oil shale in Estonia, functioning of the Estonian economy, in general, as well as the result of the economic activity of Austria's husbandry sectors.

1.2. Objectives of the research

The overall goal set up in the dissertation was to contribute to a large number of studies and debates directed to analyse and understand a variety of the interactions under 'human economic activities and the environment', established to be managed in the context of SD. It pursued internal and external objectives, which supplement and benefit each other in order to produce detailed and accurate results.

As the internal objectives[1], the study intended to analyse the overall pressures on the environment in the results of production and consumption of a main source of resources in the energy sector of Estonia, to understand how its consumption influences the total energy efficiency of Estonia's economy and how pollution is distributed among economic sectors.

As the external objectives, the study contributed to studies and debates directed at analysis of and understanding of the effects of international trade liberalisation

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[1] Those focused on Estonia.

and economic globalisation on the environment of a country-producer and country-consumer of products. GHG emissions associated with the bilateral trade of Estonia and Austria were investigated to attain this purpose. In the case of Estonia, the analysis allowed GHG emission occurred (produced) in Estonia to be itemised and covered, with a focus on GHG emissions embodied in Estonia's international trade and related to Estonia's consumption. The research was centred on energy-related GHG emissions from the combustion of primary and secondary energy sources and non-energy-related emissions occurred due to manufacturing and agricultural activities to produce goods. Non-energy-related GHG emissions due to changes in land use associated with production of goods and embodied in bilateral trade were examined on the example of the husbandry sector of Austria, which is larger than the Estonian husbandry sector[2] in terms of keeping a livestock population and livestock-related product manufacturing.

In addition, in the context of the external objectives, the present study intended to contribute to discussions on limitations and further elaboration steps for the accounting approaches in order to address, evaluate and understand the overall environmental pressure associated with economic activity in the globalising world.

More specifically the objectives were as follows:

- to apply and develop the extended LCA approach in order to measure and assess the overall environmental pressures associated with production (mining) and consumption (for generation of secondary energy sources) of a primary fuel product;
- to examine in detail, based on the enhanced LCA approach, the environmental pressure throughout the oil shale life cycle: mining, consumption for electricity and thermal energy generation, and for shale oil production;
- to analyse and address the potential of the EEIO approach to carry out accurate and complete national consumption-based energy-related and non-energy-related GHG emission inventories taking into account bilateral trade with other countries of the world;
- to identify energy-related and non-energy-related GHG emissions occurred due to production of goods and services in Estonia and to define GHG emissions intensities of commodities and economic sectors;
- to carry out an inventory of energy-related and non-energy-related (direct and total) GHG emissions embodied in the bilateral trade of Estonia with its

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[2] For example, the cattle population of Austria was 2,171 thousand heads in 2000, versus 267 thousand heads in Estonia, and Austria produced about $1,050\times10^3$ tonnes of cattle milk in 2000, versus 183×10^3 tonnes in Estonia [38].

trade partners and to investigate GHG emissions associated with the consumption of goods and services in Estonia;

- to examine and discuss the opportunities of the FCA approach to quantify GHG emissions caused by changes in land use that are associated with a product's production and consumption; and
- to define energy-related and non-energy-related GHG emissions associated with Austria's husbandry sector and to identify linkages between consumption of resources in this sector and losses in forest resources and GHG emissions associated with soybean production in Austria's trade partner countries – Brazil and Argentina.

1.3. List of original publications

The thesis is based on the following original publications, which are referred to in the text by Roman numerals.

I. O. Gavrilova, M. Jonas, K-H. Erb, H. Haberl. International trade and Austria's livestock system: Direct and hidden carbon emission flows associated with production and consumption of products. *Ecological Economics* 2010, 69, 920–929.

II. O. Gavrilova, R. Vilu, L. Vallner. A life cycle impact assessment of oil shale produced and consumed in Estonia. *Resources, Conservation and Recycling* 2010, 55, 232–245.

III. O. Gavrilova, R. Vilu. Production-based and consumption-based national greenhouse gas emission inventories: an implication for Estonia. *Ecological Economics* 2012, 75, 161–173.

1.4. Author's contribution

I. The author planned and carried out all the estimations. She interpreted the results and wrote the majority of the manuscript.

II. The author planned and carried out the majority of the estimations, excluding the examination made to investigate pressures on underground bodies of water. She interpreted the results and wrote the majority of the manuscript.

III. The author planned and carried out all the estimations. She interpreted the results and wrote the majority of the manuscript.

2. THEORETICAL BACKGROUND

2.1. The concept of sustainable development

2.1.1. The needs for sustainable development

The evolution of human society has been always closely linked with and based on natural resources [4]. For a long time, the pressure of human society on the environment was insignificant [5]. However, during the last 300 years, starting from the beginning of the industrial revolution, the pressure of society on the surrounding environment has become more intensive [25]. The increase in the global population and continuous economic growth, driven by international trade, accelerated industrial production in the early fifties of the last century [4,5]. The intensifying economic activities increased pressure on natural resource use [81], generated large amounts of emissions into the atmosphere and surface and groundwater, and accumulated waste, which required larger and larger areas for disposal and storage. The intensive environmental pressure resulted in numerous environmental disasters, which caused the suffering and deaths of many thousands of people [25]. All of these circumstances forced governments (mainly of developed countries) to act in the sixties of the last century on national and regional levels and to alleviate the environmental problems and to discuss, develop and establish national and regional environmental legislation [5].

Concerns and worries about the global environment began to emerge around the sixties of the last century as well. These views found an outlet in the organisation of the first global United Nations (UN) Conference on the Human Environment in Stockholm (Sweden) in 1972 [42]. The conference prepared the first steps for the further development of policies aimed at better governance of environmental issues compatible with continuous economic growth [5]. The latter priorities were combined in the Brundtland Report, entitled *Our Common Future*, which was commissioned by the World Commission on Environment and Development [112]. The report formulated multi-level (e.g. industry-based, national, global) interrelations between the main aspects (dimensions) of human development: economy, social and environment, and stressed the importance of taking into account the priorities of very long-term development, and the responsibilities of the present generation of people to future generations. The synergistic formulation of these interrelations and aims was combined under the concept of sustainable development. The definition presented in the Report has become a compulsory part of the environmental lexicon [42].

The next steps and actions towards SD were made at the UN Conference on Environment and Development in 1992 in Rio de Janeiro (Brazil), known as the Earth Summit [42]. The action programme was named Agenda 21 [113]. The Agenda called on countries to develop policies that can ensure the balanced interaction of human economic activities and environmental protection [42]. The fundamental principles and main actions towards SD were reiterated at the World Summit on Sustainable Development Conference (WSSD), held in Johannesburg in 2002 [66] and became an inherent part of the process of strategy development and decision-making on the national and global levels, as well as on the level of individual industrial and economic sectors.

2.1.2. Defining sustainable development

The definition of SD provided in the Brundtland Report is as follows: "*Development that meets the needs of the present without compromising the ability of future generations to meet their own need*" [112]. These "needs" are defined in a broad sense by a wide list of terms (aspects): continuous economic growth and increase of the population's wellbeing, needs in democratic principles, needs in clear air and water and in the availability of natural biodiversity, etc. These needs were structured and aggregated into three 'pillars' (dimensions) of SD: (1) economic; (2) social; and (3) environmental. Balance among the SD dimensions is vital for establishing and guaranteeing quantitative and qualitative economic growth.

In the process of balancing economic and environmental issues, trade-offs and compromises should be made, and synergy found on all levels of economic activities: on the level of an individual industry or enterprise, on the national level (e.g. setting limitations for emissions into the air and carrying out measures to reduce emissions) and on the global level through the development and ratification of international conventions, such as the Convention on Biological Diversity, Montreal Protocol on Substances that Deplete the Ozone Layer, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, the Kyoto Protocol, etc. Multi-level actions reinforce and benefit each other and could form the most effective practical policies towards a sustainable future.

The following environmental problems were selected for being addressed and managed on all levels of human activities, including the global level [113,118]:

- Protection of the atmosphere and climate system;
- Protection of the quality and supply of water resources;
- Environmentally sound management of toxic chemicals, solid and hazardous waste and sewage-related issues;
- Promoting sustainable agriculture and rural development;
- Planning and management of land resources;
- Combating deforestation; and
- Preserving biological diversity, etc.

In addition, several environmental problems of selected industries have been recognised as important. For example, the need to increase the efficiency of use of fossil fuels and production of electricity and thermal energy has been pointed out. This sector is a large source of GHG emissions into the atmosphere and an efficient method of consumption and production of energy would allow emissions of GHG and other gases and substances into the atmosphere to be reduced [7,16,18,113]. An increase in the efficiency of use of resources and materials and further development of pollution-abatement technologies in order to reduce emissions into the atmosphere and minimisation of the consumption of resources and waste generation in the industrial and transport sectors are of the same high priority as the tasks mentioned above [8,15,113]. There is a serious need in promoting less polluting and more secure extractive activities in the mining sector [8,12,113]. Special attention should be paid in the agricultural sector to the implementation of sustainable land use management and conservation of biodiversity, reduction of emissions into soil, water and air, and relieving climate issues through enhancing carbon stocks in soils and biomass [11,17,113].

Needless to say, searching for the most valuable trade-offs, making rational decisions and planning and implementing activities to minimise pressures on the environment are possible only if they are based on reliable, accurate and well-defined data. The data of the quality mentioned could be obtained as a result of developing and implementing the accounting approaches developed for SD.

2.2. The survey of measuring approaches

2.2.1. Accounting framework under SD

To understand and manage the complex of the interconnections of the three dimensions of SD, their interdependence and interference, to trace the changes in these interconnections and to evaluate the results of the activities carried out, an appropriate accounting framework, which allows assessment, measurement and reflection of all these interactions, is required [45].

There are two accounting principles recognised as measuring and evaluating the development and its status in relation to the principles of SD: (1) indicators; and (2) accounting approaches (Figure 1).

SD-indicators are used mainly for the purpose of communication of the status of development and performance control; as a rule they provide condensed and aggregated information in a visualised focussed manner to policy-makers and the public regarding the sustainability[3] of a society, national economy, industry or company or even city or village community, etc.

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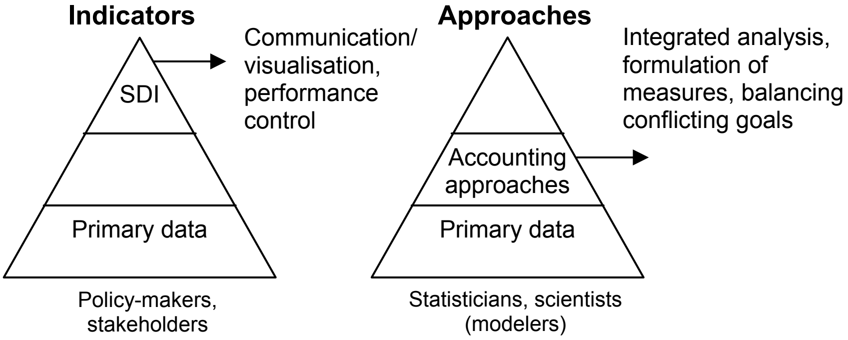
[3] "*Sustainability is the property of a thing being sustainable*" [51]



SDI – Sustainable Development Indicators

Figure 1. Accounting principles for the assessment of the development and relations to the principles of SD (adapted and modified from [105]).

The accounting approaches (inventories, input-output models, etc.) aim at comprehensive and reliable quantitative description and analysis of a system, etc., such as to analyse in detail the interrelation between the economy and the environment, or between the manufacturing process and environment. The accounting approaches are in use of scientists-modellers and statisticians [45,105].

2.2.1.1. SD-indicators

The development of SD-indicators was initiated among others by the UN Commission for SD [113]. To date, the Commission developed a set of about 96 national indicators for the assessment of sustainability [116]. In addition, the European Statistical Office (the Eurostat) and the Organisation for Economic Co-operation and Development (OECD) has developed its sets of national-level indicators [34,86]. The national indicators include information on equity in income distribution, the health well-being and living conditions of society, educational opportunities and security of society, population change, structure of the economy, consumption and production patterns of society, emissions into the atmosphere, land use, management of biodiversity, health of marine ecosystems and the availability of fresh water resources, etc. [34].

In addition to the national-level SD indicators, the elaboration of industry-oriented indicators has also taken place [47]. The latter allow for assessing the level of sustainability of industrial sectors and tracking changes (e.g. improvements) over time. The calculation of industry-oriented SD indicators is performed based on data obtained from industries and as a result of the use of accounting modelling frameworks.

2.2.1.2. SD-accounting approaches

In parallel with the elaboration of the SD-indicators, the development of a conceptual and integrated economic and environmental accounting system (SEEA) was launched by the World Bank and the UN Environment Programme (UNEP) at the lead of the London Group in 1993 [114]. The revised version of the SEEA was published in 2003 [115]. The SEEA mainly focuses on assessment of the interactions of the economy and environment and includes accounting of physical flows of energy and natural resources and a methodology of determination of effects due to the implementation of environmental policies, introduces accounting of economic value of stocks of natural resource stocks, etc. [115]. Technically, the SEEA has integrated environmentally extended input-output analysis (EEIO), physical input-output analysis (PIOA), life cycle assessment (LCA), material flow analysis (MFA), etc. To date, Input-Output Analysis[4] (IOA) and MFA accounting have been introduced to the national statistical systems of the European Union (EU), and by the Eurostat.

In addition to the accounting approaches established in the SEEA accounting framework, a wide number of accounting approaches have been developed to evaluate the interactions in the framework of the SD on different levels: from industry-oriented to national. A short list of them is as follows: Environmental Impact Assessment (EIA), Sustainability Assessment (SA), Multi-Criteria Decision Analysis (MCDA), Full Carbon Accounting (FCA), Cost-Benefit Analysis (CBA), Eco-Efficiency Analysis (EEA) and Social Life Cycle Assessment (SLCA), etc. [65]. Each of the accounting approaches has advantages and disadvantages for assessing interactions between environmental, social and economic dimensions and relies on different assumptions and covers different SD aspects.

Three accounting approaches were examined in detail in the present dissertation. The choice of the approaches for the consideration was stipulated by the objectives set up in the studies.

Life cycle assessment

Life cycle assessment (LCA) is defined as "*compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"* (Figure 2, [61–65]). In other words, LCA is a tool to analyse materials' efficiency, energy use and environmental pressure of product processing at all stages in their life cycle – from the extraction and production of resources and energy used in the manufacturing process, production of products (tools) needed for the production of the product, and final manufacturing of the product. The processes and stages related to a product's life cycle depend on the

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[4] A basis for the EEIO accounting approach.

system boundary defined, i.e. the system of unit processes included in consideration within LCA.

There are four phases of LCA approach [61–65]: (1) *the goal and scope definition phase*, which clearly defines reasons for carrying out the study, the intended audience (i.e. to whom the results of the study are intended to be communicated), the system boundary of a product, main processing units, assumptions made, data quality and adjustments made, etc.; (2) *the inventory analysis (LCI) phase*, which involves the compilation and quantification of inputs and outputs for a product throughout its life cycle; (3) *the impact assessment (LCIA) phase*, whose aim is understanding and evaluation of the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product; and (4) *the interpretation phase*, which concentrates on the findings of the analysis, the environmental impact assessment and evaluation of the goal and scope of the analysis in order to reach conclusions and recommendations.

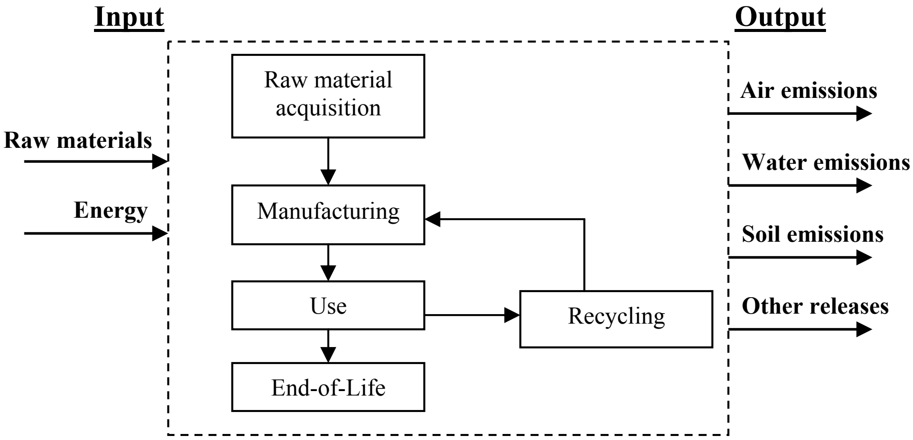

Figure 2. The graphic description of LCI approach (modified from [99]).

The algorithm (procedures) for performing LCA of a product or manufacturing process is standardised by the International Organisation for Standardisation (ISO) [64] and published [61,62,63].

In addition to the international methodology (standards) developed and accepted by the ISO, a large number of supplemental handbooks, reports, working documents and papers has been published in order to explain how to perform LCA of one or another economic sector or product (commodity) production branch. The differences and peculiarities of the economic sectors and products manufactured should be taken into account in carrying out LCA. Since, for example, manufacturing processes of food products are different from the process of chemical product manufacturing and from mineral production, etc.

Moreover, production processes of the same product can be different within the same economic sector – e.g. electricity can be produced in the energy sector using different resources and technologies: from fossil fuels, hydropower, biomass or wind, etc. This fact stipulates additional areas to be assessed. For example, the environmental impact of fuel production processes should be certainly addressed in full LCA of the processes of electricity generation from fossil fuels. In case of the assessment of the processes of electricity generation from wind, the environmental impacts of the functioning of a compensating power plant should be included [125]. Application of LCA approach for mining activities faces some specific aspects that require being addressed as well. The focus, during the LCA process, shall be placed on the environmental impact caused by the activities on the land and aquatic resources of a mining region [130]. Implementation of LCA for products of the agriculture sector also has its distinguishing feature. Agricultural systems are related to each other, e.g. changes in feed for livestock may cause changes in crop production. The agriculture sector depends on countries' land use policies, which determine the capacity of carbon sequestration via a decrease or increase of cultivated areas [49]. These circumstances should be taken into consideration in the framework of the LCA methodology for agriculture-related products.

However, in spite of the large number of supplemental guidelines and handbooks developed to improve and enhance the LCA methodology for products of different economic sectors, several limitations can be noted [48,50]. Two of these are presented below:

- spatial limitation – the results obtained due to application of LCA are translated to the global scale (e.g. due to use of coefficients on global warming potential to emissions of GHG); however, the actual environmental impact occurring in a region is not addressed properly in the framework of the accounting approach. In other words, the sensitivity of a region against environmental impacts is not taken into account;
- temporal limitation – results obtained due to application of LCA are steady-state, they usually do not take into account changes of technology or production process over time. In addition, the results do not reflect the overall pressure associated with a product's production over a certain time and a scale of the total contribution to the environmental pressure occurred on regional or national levels.

These limitations should be solved (taken into account) in order to provide accurate and transparent data required to make the most effective decision towards the goals of SD on product or industry-oriented levels.

Environmentally extended input-output analysis

The method of Input-Output Analysis (IOA) was developed by Nobel laureate W.Leontief in the thirties of the last century. The approach focuses on description and analysis of the production structure of the economy. In other words, IOA provides a comprehensive picture of the output of commodities by each sector of the economy, the use of domestically produced and imported commodities of one sector for intermediate consumption to produce commodities in another sector of the economy, the final consumption of commodities within the economy and commodities exported abroad [30].

Algebraically, the relationship between the total output of sectors and the intermediate and final demand for commodities can be described as follows (1):

$$x = A \cdot x + y, \tag{1}$$

where A is the matrix of intermediate consumption, which defines the intermediate input requirements for each commodity (domestically produced and imported) of each industry to produce one unit of commodity output in another industry (called the technology matrix), x is the vector of output and y is the vector of final demand (i.e. domestic and export). The solution of the linear equation system (1) is (2).

$$x = (I - A)^{-1} \cdot y_{,} \tag{2}$$

In (2), $(I\text{-}A)^{-1}$ is called the Leontief inverse matrix and reflects the direct and indirect requirements in commodities for intermediate consumption for the production [Publication III].

National monetary input-output tables (IO tables) have been compiled for more than 40 countries by the Eurostat [31] and by the OECD [85]. In addition, a wide list of institutions supports development of IO tables. Namely, the IDE/JETRO[5] developed IO tables for nine countries of Asia, the University of Sydney has a dataset developed including IO tables for about 130 countries, GTAP[4] – for 113 countries [127]. Hence, to date, there is a solid basis developed for further investigation of the interactions between the economy and the environment under the SD concept in the IO framework.

Extension of standard monetary IO tables with data on pollution emissions, waste, resources used (i.e. environmentally extended input-output analysis (EEIO)), which are widely available in national as well as in international datasets, allows for assessment of direct and indirect environmental pressures associated with each sector and an understanding of how the environmental inefficiency/efficiency of one sector of the economy affects other sectors, in general. Mathematically, the extension of the approach is organised as follows: rows showing environmental pressure (e.g. emissions, waste generated, etc.) are added to the monetary IO table, which enables the estimation of a direct

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[5] IDE/JETRO: Institute of Developing Economies/ Japan External Trade Organization; GTAP – Global Analysis Trade Project database.

emission coefficient for each commodity, and simultaneous calculation in the domestic Leontief inverse matrix provides the total emission coefficient (i.e. direct and indirect intensities) of each commodity. The standard IO table and its extension are visualised in Figure 3.

Economic activities	Use of products (activity groups)	Final consumption	Export	Total output
Production activities (activity groups)	Intermediate consumption	Final consumption	Export	Total output
Output				
Import				

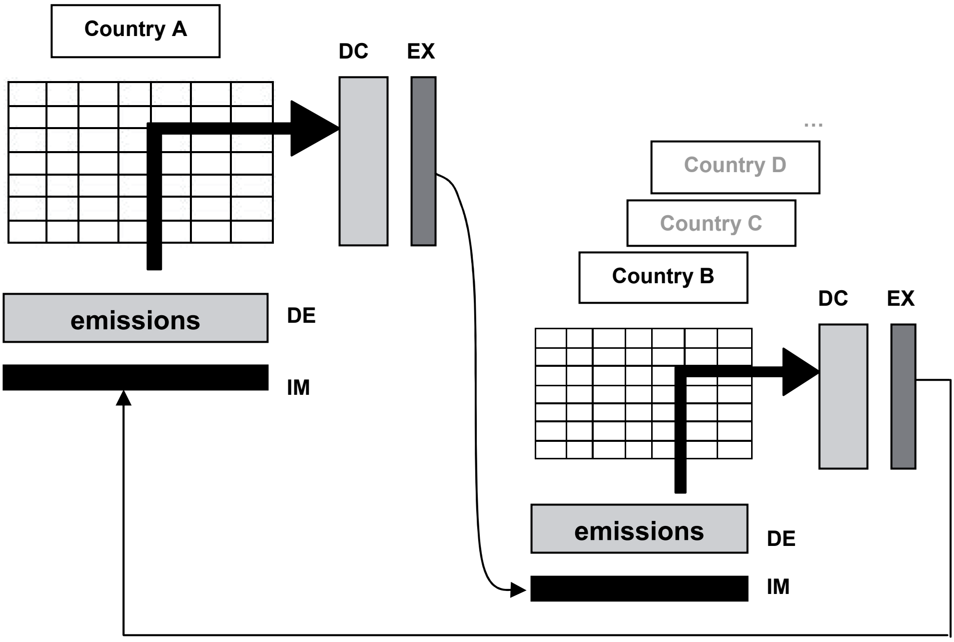
Extensions:
-Primary natural resource input
- Emissions output
- etc.

Figure 3. A graphic description of the IO tables and their extension with environmental data (modified from [2,111]).

The extended IO tables are widely used to compile production-based and consumption-based GHG inventories. The basic difference of the two approaches is explained graphically in Figure 4. Data on international trade and the Emission Embodied in Bilateral Trade (EEBT) or the Multi-Regional Input-Output (MRIO) approaches are usually employed in completing the inventories.

The EEBT and MRIO approaches differ in how they treat imported commodities and, consequently, in the sources of GHG emissions embodied in them. The EEBT does not distinguish between different uses of imported commodities, i.e. whether they are used for final consumption or for intermediate consumption to produce commodities that could be domestically consumed or exported. In other words, the EEBT approach assumes that GHG emissions embodied in commodities imported to a country remain within the boundaries of the country and are not "(re)exported" with commodities in the production process of which imported commodities were used, i.e. the overall GHG emissions "imported" to a country are considered "consumed in the country". In the framework of the MRIO approach, GHG emissions embodied in commodities imported to a country are split into two parts: for final consumption and for intermediate manufacturing to produce commodities, and accounts for GHG emissions that are "(re)exported" from a country-importer. Therefore, the approach allows the examination of a "feedback" effect in GHG emissions associated with the trade where GHG emissions are embodied in imported commodities that are (re)exported back to the country of origin from the destination country [109, Publication III]. The EEBT is used mainly to illustrate GHG emissions (or environmental impacts) embodied in the bilateral trade of the countries, and the

MRIO approach is better suited to demonstrate GHG emissions (or environmental pressures) on the global scale. On the whole, the difference in the consumption-based GHG emissions inventories completed using the two methods may reach approximately 20–30% for some countries [93,94].



DC – Domestic Consumption, DE – Domestic Emissions, IM – Import, EX – Export.

Figure 4. Graphic presentation of the calculation in the framework of the consumption-based inventories (modified from [44]).

The EEIO approach is considered to be an advanced tool and the most employed approach to complete consumption-based GHG emissions inventories. Nowadays, the EEIO approach is, practically, a sole approach, which assesses the interaction between the economic activities of a country-consumer and pressures on the environment around the world. In other words, the GHG emissions accounted under the approach "goes far away from the boundaries" of a country. Nevertheless, it should be mentioned that nowadays, mainly energy-related GHG emissions are accounted for; non-energy-related emissions are usually omitted from the studies performed in the framework of consumption-based GHG emissions inventories. The approach has a list of limitations, which are associated with the methodology of the approach developed as well as related to data used in the estimates – i.e. uncertainties [52,75,94,126]. Understanding of uncertainty information is primarily needed in order to identify areas in which the inventory might need improvement in the future in order to estimate GHG emissions in internationally traded commodities and to establish consumption-based GHG national inventories of countries around the world.

Full carbon accounting

The full carbon accounting (FCA) approach is focused on the interaction of economic activities and pressure on a climate system mainly through CO_2 emissions. Needless to say that to date, there has been no consistent definition (scheme) of the carbon accounting approach, since different authors use different calculation algorithms for accounting of carbon emissions and removals (or CH_4 and CO_2 recalculated to carbon) depending on the concrete aims of the studies. For example, the FCA approach is used to account for carbon stock in soils and organic carbon mass per unit of ground area [43], to examine emissions and removals and sinks associated with land use, including those not covered under the UNFCCC inventory [83], to evaluate all emissions related to the production of product or manufacturing processes, based on the main principles of the LCA approach [89] (see review in [108]), etc. The diversity in the definitions and implementation of the ‘carbon accounting’ approach allows all types of GHG emissions to be covered on different levels of economic activity: product, local, regional.

The assessment of GHG emissions and carbon accumulations performed in the present dissertation was based on the principles established in LCA approach, presented in Figure 5. The method used is also known as LCA GHG analysis [89]. The approach is defined as the life cycle of GHGs emissions – direct and indirect energy-related and non-energy-related upstream and downstream emissions from production and manufacturing activities and waste stored (i.e. those GHG emissions and removals that occurred in six sectors of the IPCC Guidelines [58,59,60]). However, in our particular case the approach considers only direct GHG emissions from changes in land use [89,106].

Implementation of the FCA approach includes three phases: (1) assessment of all the impacts on climate change related to direct and indirect production activities (e.g. energy supply for electricity and heat generation, fuel combustion in the process of transportation, growing livestock and other agricultural processes, etc.; with the exception of indirect activities, which forced changes in land use). In other words, the approach focuses on all upstream emissions associated with production of a product and downstream emissions resulting from waste, which is generated in the process of product manufacturing; (2) collection, validation and classification of data, and calculation of GHG emissions (i.e. direct and indirect); and (3) scaling up of emissions to represent 100% of the total GHG emissions associated with a product. The last phase helps to evaluate the contribution of all sources of emissions to the total emissions associated with a product or economic activity.

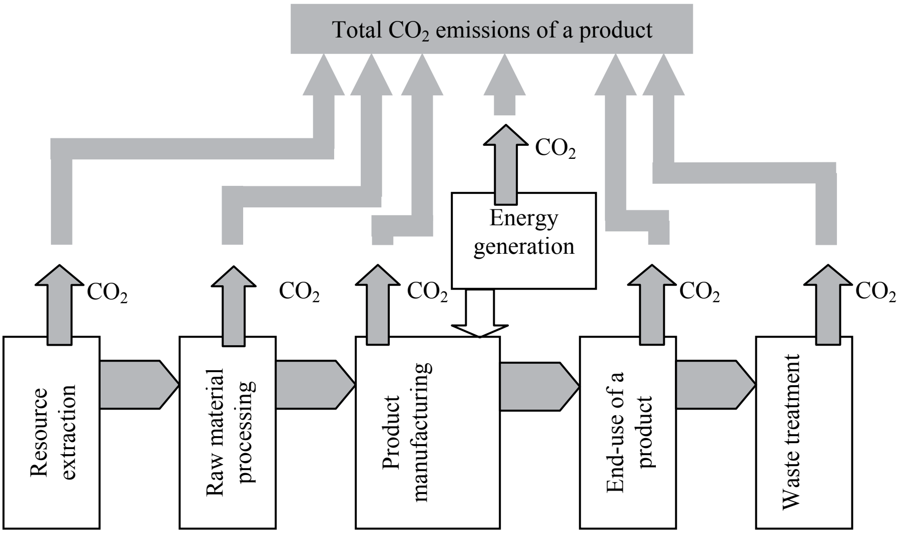


Figure 5. A graphic description of the FCA approach (modified from [104]).

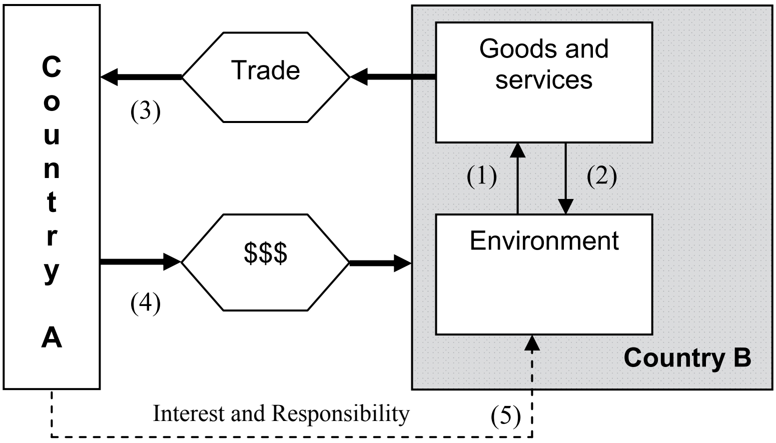
Detailed accounting of GHG emissions associated with a product or national level allows the most emission-intensive process in production chain to be analysed and understood, and is considered to be the main advantage of the approach. Nevertheless, because the FCA approach was developed on the basis of LCA, the method includes several of its limitations mentioned earlier (i.e. temporal and spatial). In addition, the approach does not take into account emissions resulting due to indirect changes in land use in calculations of GHG, which could lead to emissions of significant size being neglected.

2.3. Measurement challenges

About 40 years has elapsed since the organisation of the first global conference on the environment in Stockholm, and more than 20 years has passed since the establishment of the Agenda 21 [113]. These decades saw significant quantitative and qualitative changes in our global society: the world's population has remarkably increased – from 4,077 million people in 1975 to 6,896 million people in 2010 [38,81], and the level of human well-being has grown significantly in many countries around the world [84]. The negative pressures on the environment have continuously grown as well, e.g. the increase of consumption of primary energy sources and increase of crop production areas due to decreases in forested areas and increases in pollution emissions into the surrounding environment, etc. [38,81,86]. Moreover, during these years, the countries of the world have become more interconnected and interdependent on each other due to international trade. The trade of goods increased by four times by 2006 compared to the end of the eighties of the last century [128]. The trade liberalisation process has allowed many companies of advanced economies to produce goods outside their home countries, often in developing countries with cheap labour, low resources or capital costs, lenient pollution control, etc., for import into their economies. The same scheme is observed, if companies operate supply chains that stretch far beyond their domestic markets [14]. This means that long geographical/physical distances between producers and consumers have become commonplace [69] and global clusters of countries-consumers and countries-producers have been formed – however, with frequently "unfair" distribution of roles in the clusters. For example, the developed countries, which contribute about 15% of the global population, account for about ¾ of global consumption. The United States alone, with 5% of the global population, consumes about 30% of the world's resources [5]. An average European citizen uses about four times more resources than one African inhabitant and three times more than one citizen in Asia, but half of that of a US, Canadian or Australian citizen [21]. As Brazil, China and India are becoming more and more important world manufacturing countries [121], and the goods are still consumed mainly in the countries of the developed world, it is also making transport of goods almost commonplace.

The "distances between producer and consumer" stipulated the "distances" between the dimensions of SD on the national level, which can be described as follows: a country-producer (Country B in Figure 6; e.g. a country with lower cost of labour, resources costs, lower standards of pollution control, etc., than Country-consumer A) uses the resources to produce goods and services, which is also accompanied with emissions into the atmosphere, water and waste generation. However, the product is exported from Country B and is consumed by consumers in Country A. It means that environmental impact is "left" within the boundaries of a country-producer (Country B) and the country-consumer (Country A) "avoids" being responsible environmental impacts associated with product manufacturing. It is true that Country-producer B is earning money for the production, but in the situation described with low environmental standards in the countries-producers significant leakage flows of environmental pressures are currently not taken into account in the framework of the accounting in the framework of the SD concept.

Hence, nowadays, globalisation can be considered as the fourth dimension of SD, which should be addressed to collect specific information and to make decisions on further development. There is a remarkable need to analyse the consequences of globalisation and international trade on the notion and status of SD, and to develop an appropriate accounting framework for monitoring and controlling these global processes.



(1) Country B uses natural resources to produce goods and services (e.g. minerals, fossil fuels, water).
(2) Production of goods and services by Country B is accompanied by pressure on the environment (e.g. emissions into air and water, waste generation, etc.).
(3) Country B imports goods and services to Country A.
(4) Country A makes payment to Country B for goods and services imported.
(5) Country A imports goods and services produced in Country B, which are the cause of the environmental pressure Country A is in fact "responsible" for in Country B. It is a question whether the compensation (4) is sufficient to justify and compensate the worsening of the environmental situation in Country B.

Figure 6. A simplified scheme of the economic and environmental interaction of two countries in the conditions of globalisation and trade liberalisation (modified from [69]).

The EEIO approach is the sole approach of those considered in the present dissertation in detail, which allows the issues related to globalisation to be taken into account on country-level (i.e. environmental pressure associated with international trade). LCA and FCA focus on the identification and analysis of the interaction of economic activities (oriented on product/sector production) and the environment inside the countries. Nevertheless, the results obtained in the framework of the application of these approaches are considered to be a solid basis, which can (shall) be used to determine the overall environmental pressure embodied in products internationally traded and to figure out the "responsibility of consumers for environmental pressure". Hence, there is a need to elaborate the limitations of LCA and FCA approaches as much as possible and to minimise the uncertainties of the EEIO approach. Further clarification of the methodological issues would allow accurate, reliable, well-defined, transparent and comprehensive data to be obtained, which would facilitate reliable determination and evaluation of the environmental pressures associated with production and embodied in exported/imported commodities.

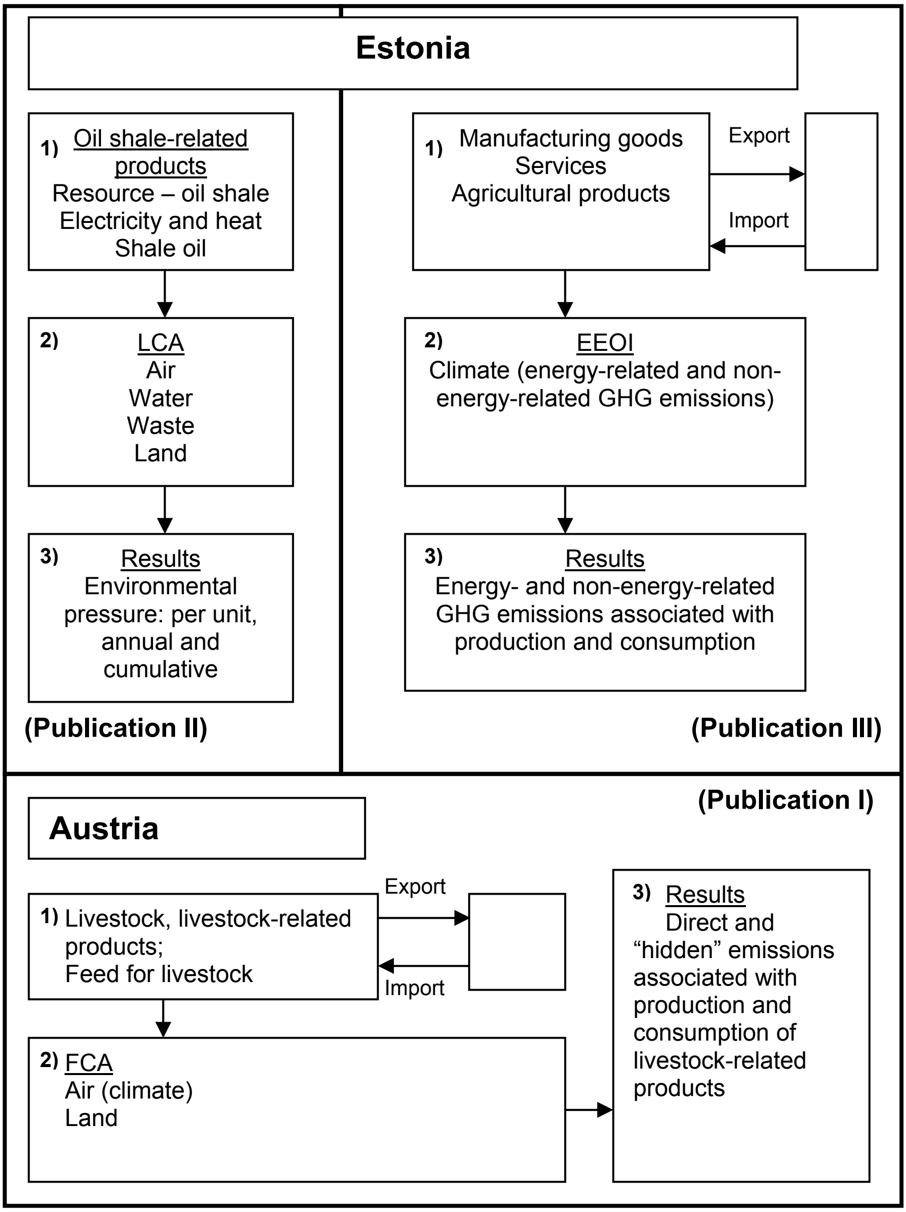
3. MEASURING SUSTAINABLE DEVELOPMENT

3.1. A overview of the research procedure

The focus of the dissertation was placed on three case studies, two of which were centred on examining the environmental pressures associated with production, bilateral trade and consumption of commodities in Estonia and one case study was concentrated on the husbandry sector of Austria (Figure 7).

The environmental pressures, associated with production and consumption of Estonian oil shale-related products, were examined using an enhanced methodology of LCA approach. The enhancement of the approach was provided in LCI phases: in addition to environmental pressure per unit of oil shale-based products, the annual impact from the operation of oil shale facilities and cumulative environmental pressures that have accumulated since the commencement of their operation were considered. This allowed the overall environmental pressures omitted up to now due to the limitations of the approach to be taken into account [Publication II]. Estonian oil shale-related products were chosen for the investigation because these products play an important role in the economy of Estonia: the products are used within Estonia as well as exported abroad, and the production processes of oil shale-related products also determine the environmental situation of the whole country of Estonia. The wide availability of reports and scientific publications allowed the enhanced analysis to be performed.

Two types of national Estonian GHG inventories were compiled as the second case study [Publication III]. Energy-related and non-energy-related GHG emissions associated with production and consumption of commodities in Estonia were examined with the EEIO and the EEBT approaches. This is the first time such a detailed analysis of these inventories has been completed for Estonia. As to date Estonia's national production and consumption-based inventories have been performed only in the framework of global-scale models [3,6,95,94,102], which do not provide a broader understanding of the factors (e.g. trade structure, volume, trade partners) determining differences in the levels of emissions of an individual (small) country due to the international trade. In the present case study, emphasis was put on the analysis of the energy-related GHG emissions intensity of commodities produced in Estonia and Estonia's trade partners and on the values of energy-related and non-energy-related GHG emissions embodied in the bilateral trade of Estonia.



1) the subject of study; 2) the method employed and the environmental pressure examined for the studied country as well as in the country's trade partner; 3) the results obtained on evaluating of environmental pressure.

Figure 7. The case studies carried out and their research components.

GHG emissions from production and consumption of livestock, livestock-related products in Austria and Austria's trade partners were analysed in the third case study [Publication I]. The main principles of the FCA approach were employed in the estimations, and evaluation of the methodological limitations was stressed (i.e. indirect GHG emissions resulting from changes in land use were estimated). In addition to GHG direct emissions associated with the production of livestock and livestock-related products in Austria and its trade partners, direct and "hidden" (indirect) emissions, which occurred in Brazil and Argentina due to deforestation to produce feedstuffs (soybeans) for export to Austria, were evaluated and analysed.

The data employed in these three case studies were obtained from international datasets [35,38,57,120], as well as from country-specific reports and scientific articles.

3.2. Life cycle environmental impact of oil shale produced and consumed in Estonia (Publication II)

3.2.1. Framework overview

The system boundaries of the study

The Estonian oil shale complex (hereinafter referred to as 'the complex') consists of four branches and thirteen facilities. The flow diagram visualises all the major branches of the oil shale complex as follows:

1) oil shale resource mining (including the enrichment stage);

2) oil shale-based electricity and heat generation;

3) oil shale retorting (i.e. shale oil production); and

4) oil shale combustion in the process of cement production (referred as 'Cement production' in Figure 8).

Cement production was not analysed because of the insignificant volume of oil shale consumed in the process (i.e. 3% of the total quantity of oil shale consumed) and lack of available data. Imports and exports of oil shale and related products were included in the analysis. Emissions to the environment from oil shale transportation were ignored in the study because of a lack of available data [Publication II].

The study focused on twelve facilities in the complex (Figure 8):

1) four oil shale mining facilities, including the enrichment plants (all operated by Eesti Põlevkivi Limited (EP Ltd.), a subsidiary of Eesti Energia Ltd. (EE Ltd.);

2) four power plants (PPs): Balti, Eesti (Narva PPs), Ahtme and Kohtla-Järve (Kohtla-Järve PPs), all owned by EE Ltd. Emission flows associated with the Sillamäe combined heat and power plant (CHP) operating on oil shale were omitted because of a lack of available data and the small volume of oil shale used; and

3) three shale oil factories: the Narva, Viru and Kiviõili oil factories (operated by EE Ltd., Viru Keemia Grupp Ltd. and Kiviõli Keemiatööstus Ltd., respectively).

All facilities are located in Ida-Viru County in the North-Eastern part of Estonia (Figure 9).

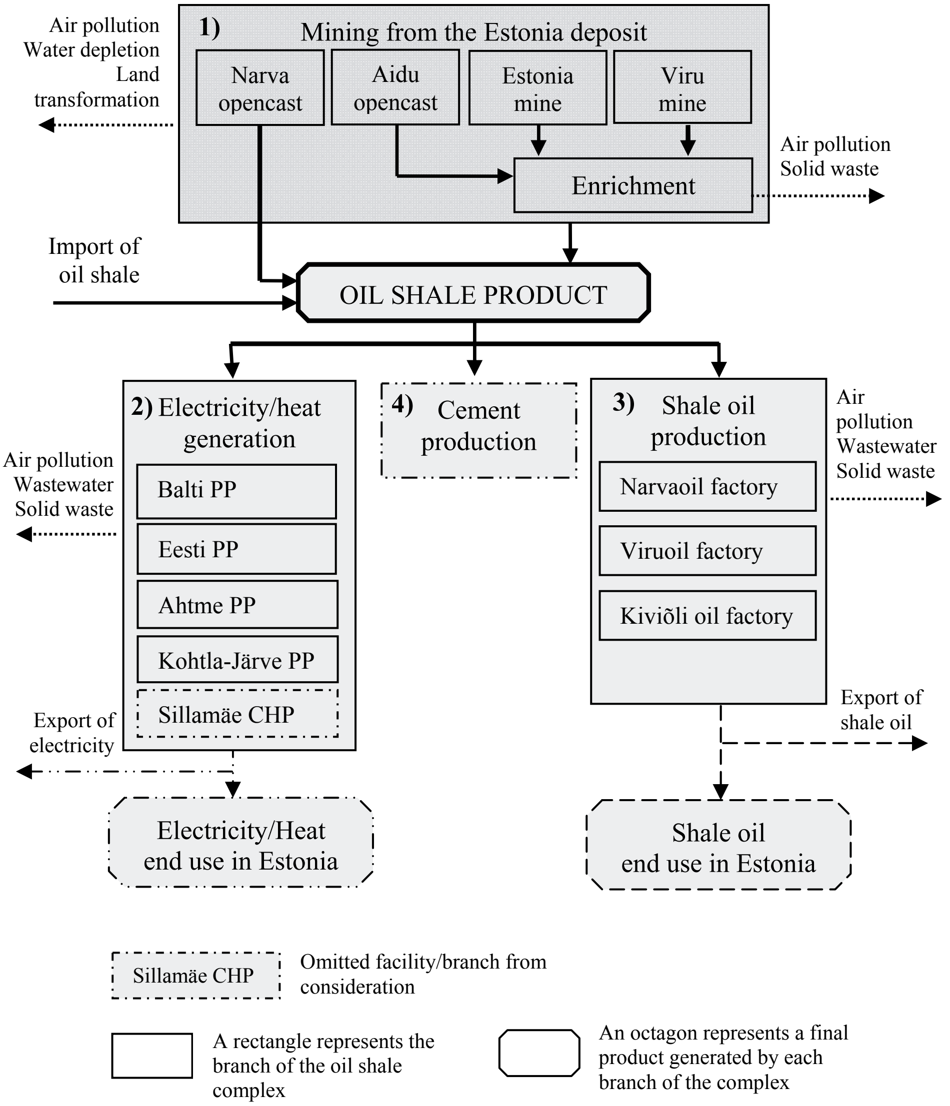
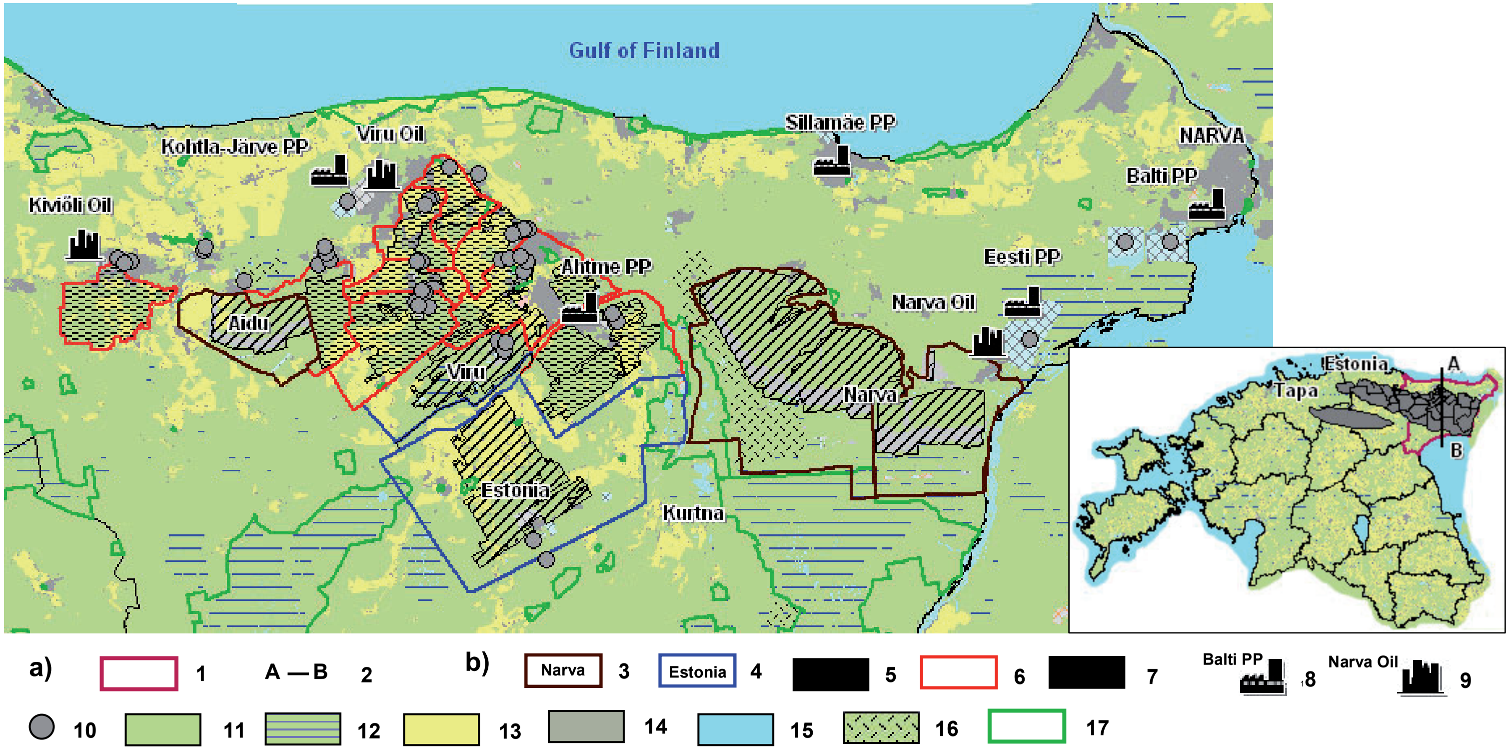


Figure 8. Flow diagram for the life cycle of oil shale produced and consumed in Estonia [Publication II].



a) *Location of oil shale deposits:* Estonia – Estonia oil shale deposit; Tapa – Tapa oil shale deposit; 1 – border of Ida-Viru County; 2 – line of hydrogeological cross-section (see Fig. 3 in Publication II); b) *Facilities of the oil shale complex:* 3 – border of opencast mine in operation; 4 – border of underground mine in operation; 5 – mined-out area; 6 – border of closed mine; 7 – exhausted and flooded area; 8 – electricity and heat generation power plant; 9 – shale oil producing factory; 10 – waste disposal site. *Land cover:* 11 – forestland; 12 – wetland; 13 – agricultural land; 14 – urban area; 15 – body of water; 16 – peat extraction area. *General:* 17 – border of nature reserve; Kurtna – Kurtna Landscape Reserve; NARVA – city.

Figure 9. Location of oil shale deposits, facilities of the complex producing and consuming oil shale, and waste disposal sites as of 2002.

Functional unit of the study

The choice of unit (functional unit) for measuring and describing products and processes in LCI is an important aspect of the analysis. A commonly accepted functional unit is defined by the performance or services of the functional outputs of a product system delivered to customers [62]. The reference flows (i.e. input and output flows) calculated allow assessment of the generation of pollution and waste per unit of the product and enable the products to be treated and compared with alternative products of the product market (e.g. coal-based electricity and heat, crude oil in the present case). The commonly accepted calculation process examines the values of the reference flows, but the values do not address localised (spatially defined) pressures on the environment, by identifying and assessing spatial pressure of a branch/facility in a specific region [48]. In other words, the environmental sensitivity of a region is usually not taken into consideration in the framework of LCA approach. Hence, the pressure and negative changes in the environment are left unexamined. But this was not the case in the present work [Publication II].

The functional unit chosen for this study was the energy value in GJ of the final product generated by each branch of the complex (i.e. oil shale, oil shale-based electricity, heat energy and shale oil, (i) in Figure10). In the framework of LCI, the focus was put only on the consideration of input and output flows associated with the environment (i.e. pollution emissions into air, water and waste generation, surface and underground water extraction and land transformation), and input flows required for the process's operation (e.g. chemicals and other materials, equipment, etc.) were omitted from the study. Moreover, in the process of broadening LCA in order to solve the limitations of the approach, annual pressures on the environment ((ii) in Figure 10), which allowed assessment of the contribution of a facility/branch to the total pollution in Estonia and cumulative environmental pressures of the facilities (or the branches) accumulated since the commencement of their operation (i.e. the incremental environmental pressures from the past and the present; (iii) in Figure 10), were included and assessed. The evaluation of the cumulative pressure allowed the scale of the environmental changes occurred in the region to be understood and assessed because of the operation of the complex. Focusing on cumulative pressure is especially important in evaluating changes of land topography and the hydro-geological balance and water quality of the region due to the operations of the facilities of the complex, and land use changes and contamination of the surrounding environment due to waste disposal [Publication II].

Figure 10. Functional units employed in the present study.

Inventory data

Data of 2002 were used to analyse the environmental burden per functional unit. Additionally, data of 2001 and 2006 were used in some specific cases to explain and justify choosing the most appropriate data or to demonstrate emission alterations due to important technological changes and environmental protection activities introduced. Data of 2007 were used, as the best available, to evaluate the pressure of oil shale mining on water resources.

More than 200 reports and scientific articles were referenced to reliably evaluate the cumulative pressure on the environment, which was caused by the long-term operation of the facilities of the complex.

3.2.2. Oil shale production and consumption in Estonia

About 13 million tonnes (13×10^6t) of commercial oil shale were consumed in Estonia in 2002, which included 0.7×10^6 t of oil shale imported from Russia. Of this figure, 80% was used for electricity and heat generation, about 17% was consumed for shale oil production, and the rest was used in the cement industry [24,67].

3.2.3. Oil shale mining

Oil shale mining is carried out in Estonia using a surface method (in the Aidu and Narva opencast mines) as well as an underground method (in the underground mines in Estonia and Viru) (Figures 8,9).

On average, the extraction of 28 GJ of oil shale (i.e. 3.5 t) causes the transformation of one square meter (m^2) of land of the deposit. Annually about 4 square kilometres (km^2) of land are transformed into “disturbed mined-out land” as a result of oil shale mining operations. To date, the whole period of oil shale extraction (i.e. more than 90 years) has resulted in the “transformation into disturbed mined-out land” of about 424 km^2, which comprised 12.6% of Ida-Viru County’s territory in 2002 [67]. Of this, about 87 km^2 of the area “disturbed” by the underground method was classified as subsided where the relief was changed as a result of underground pillars collapsing, 36 km^2 were defined as stable and 150 km^2 were defined as unstable, 79% (72.4 km^2) of which was liable to subside in the coming decades [100]. The failures of underground pillars took place under roads and agricultural lands, forcing future generation to change their land use practice.

Two major types of solid waste are generated in the process of oil shale mining and enrichment: a covering layer (i.e. overburden) and solid waste containing limestone originating from the layers intercalating kukersite beds (i.e. waste rock). About 35.5×10^{-3} t of waste rock (classified as non-hazardous waste [9]) is separated per GJ of oil shale product generated in the process of raw oil shale enrichment and is stored in heaps. During more than 90 years of oil shale use, the total accumulated volume of solid waste (i.e. waste rock) from oil shale mining is 165×10^6 t, which is stored in 33 heaps (pyramidal cones with steep slopes and great heights) that cover an area of more than 3.4 km^2 [107]. 27% of all heaps, (i.e. 9 heaps) self-combusted between 1960 and 1980, and the average burning period was about ten years [98,107]. The leachate of burning/burned heaps contaminated the surrounding surface and groundwater with phenols [74].

The limitation of LCA was clearly observed in the case of the investigation of the environmental pressure on water resource of the region due to the process of oil shale extraction. Namely: to produce a GJ of oil shale, 1.6 cubic meter (m^3) of water (on average) must be pumped out per GJ of mined oil shale. In particular, this value is used for the comparison of oil shale with other primary solid fuels, as well as in the process of making decisions. However, the results of the LCI dissemble that the total annual amount of mine water pumped out, treated in sedimentation ponds and directed into the region's river network was 185 million m^3 (185×10^6 m^3 versus 160×10^6 m^3 in 2002) in 2007 [26]. This was 3.6 times the amount of groundwater consumed during the same period by the rest of the entire country [91,92]. According to the calculations based on the basin-wide hydro-geological model of Estonia developed by L. Vallner [122], the amount of water pumped from oil shale mines exceeded the available resource of the body of groundwater (GWB), from which water was pumped out in 2007, by a factor of five[6]. The quality of this GWB does not meet the standards of drinking water [22,73]. Therefore, the drinking water has been abstracted from the underlying GWBs in the oil shale basin. Abstraction has been from two to three-fold greater than the available resource of these GWBs over the last 60 years [72]. The result of this increased pumping is a basin-wide depression, which had induced saline water intrusion into deep GWBs. In addition, the underlying GWB contains radioactive substances, meaning a person drinking this water receives an annual effective radioactive dose ranging from 0.16–0.33 millisievert, which exceeds the recommended limit by up to 3.3 times [73]. Hence, future generations have to look for new possibilities in technological and financial areas to provide the region with drinking water. This fact is contrary to the main principle of SD – to meet the needs of future generations (i.e. clean drinking water needs).

The exhausted underground mines in Estonia are flooded (Figure 9). The total area of the "underground sea" is 220 km^2, with 170×10^6 m^3 of water contained within them. The sulphate (SO_4) content of this water increased sharply from

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[6] The 'available groundwater resource' is a term of the Water Framework Directive (WFD) [10]. It expresses the long-term natural average rate of overall recharge of a GWB. If the real abstraction from a GWB exceeds its available resource then overexploitation of groundwater takes place resulting in an excessive lowering of the pressure in aquifers and deterioration of groundwater quality. The available groundwater resources of all GWBs of the oil shale basin have been determined by investigations.

300–600 mg/l to 1,200–1,500 mg/l in the two years following flooding as a result of the oxidation products of pyrite leaching from carbonate rocks. The sulphate content has later decreased, but still remains higher than the natural background [27]. The pumped water at 1.6 m^3 (on average) per GJ of mined oil shale is discharged through pipelines to two natural sedimentation ponds from where water polluted with sulphate flows into rivers. Because of mine water pumping, the sulphate concentration is high in most rivers in the region [28], as well as in nearby lakes, which also include the 40 picturesque lakes of the Kurtna Landscape Reserve (Figure 9). The content of sulphate in some of the lakes has increased to 160–259 mg/l between 1946 and 2000 [27] (in 1937, the sulphate content of these lakes was in the range of 1–7 mg/l [101]). This pollution of surface waters of a regional character should be considered as an additional risk to the quality of the potential future drinking water system of the region.

3.2.4. Electricity and thermal energy generation

About 10.6×10^6 t (88.27×10^6 GJ) of commercial oil shale was consumed to produce electricity and heat in the PPs in 2002. Of this figure, 68% and 29% was used by Eesti PP and Balti PP, respectively; Ahtme PP and Kohtla-Järve PP, together, consumed 3% of the oil shale amount.

More than 90% of the total electricity and 16% of the total heat was produced from oil shale in 2002 [29].

Based on the final net output of energy (i.e. electricity and heat), the energy-recovery ratio of energy stored in oil shale (i.e. the efficiency of use of the resource energy by the ‘electricity and heat generation’ branch) was 29%. This value decreased to 24.1% when accounting also for oil shale losses during mining. About 50% of the total oil shale energy consumed was discharged with cooling water into the Narva artificial lake. A detailed overall flow diagram of electricity generation in the PPs is presented in [Figure 4 of Publication II].

The operation of PPs causes pollution emissions into the atmosphere: sulphur dioxide (SO_2), solid particulates, nitrogen oxides (NO_x) and carbon dioxide (CO_2) are major gaseous emissions. Emissions of SO_2, NO_x and solid particulates from all of the PPs have decreased 2.7, 1.5 and 6.3-fold, respectively, from 1990–2006 [28]. This has contributed to decreased SO_2 and NO_x concentrations in the ambient air of the region [76,77,78].

Nevertheless, oil shale-based electricity is associated with high emissions of CO_2 equivalent (CO_2eq) per GJ. Because of high CO_2 emission values from oil shale PPs, Estonia is one of the leaders in the European Union in CO_2 emissions per total primary energy supply (TPES) [35]. Undoubtedly, the contribution of Estonia to total world emissions-forced climate change is negligible (0.05% of the global CO_2eq emissions in 2005 [19]). However, taking into account the principles of equal responsibilities in front of the global community in order to combat climate change, Estonia should make maximum efforts to reduce GHG emissions.

The production of oil shale-based electricity is associated with a high level of water use for technological needs (i.e. condensing water and auxiliary water for boilers and heat networks). In 2002, the level of water use was more than five times higher than Estonia's total domestic water use [20]. Afterwards, at the Narva PPs the cooling water is withdrawn from and discharged (1.5 GJ of wasted energy per GJ of energy produced) into the Narva artificial lake. The Kohtla-Järve PPs divert cooling water back to cooling towers located on the plant territory [87].

Pollution emissions into bodies of surface water vary with annual levels of precipitation. Emissions of sulphates are dominant among the level of pollutants per GJ of energy generated by PPs [Publication II].

6.4 GJ and 6.9 GJ of energy (electricity and heat) per m^2 by Eesti PP and Balti PP, respectively, and 14.4 GJ and 16.5 GJ per m^2 by Ahtme PP and Kohtla-Järve PP, respectively, are produced per destroyed per m^2 of land. Nowadays, more than 3 km^2 of land annually is being destroyed because of oil shale mining for electricity and heat production. The land is also occupied due to waste generation and storage. About 163×10^{-3} t of ash per GJ was generated in the Narva PPs and 71.1×10^{-3} t was generated at the Kohtla-Järve PPs in 2002. The quantity of ash generated at the PPs contributed over 83% (5.3×10^{6} t) of the total amount of hazardous waste generated in Estonia in 2002 [70]. The overall amount of oil shale ash disposed in ash fields is 258×10^{6} t in area of 20 km^2 [71]. The disposal of hazardous oil shale ash leads to contamination of soil and groundwater. The pH of the highly toxic ash leachate is about 12.4–12.7. Groundwater is also polluted with oil products, phenols, toluene and xylene [107]. According to the data of the database of past pollution sites, the area of groundwater polluted by oil shale ash leachate was 9 km^2 [103, Publication II].

3.2.5. Shale oil production

Two types of retorting technologies are used in Estonia to produce shale oil in Estonia: Kiviter technology (vertical gas generator technology; in use at the Viru oil factory (Viru Oil) and Kiviõli oil factory (Kiviõli Oil)) and Galoter technology (solid-heat-carrier technology; in operation at the Narva oil factory (Narva Oil)) [129]. In tonnage-terms, more than 50% of shale oil was produced by the Viru Oil factory, the Narva oil factory produced about 30% of the total shale oil, and the remaining amount of shale oil was produced by the Kiviõli Oil factory in 2002.

The energy-recovery ratio of producing shale oil using the Kiviter and Galoter technologies was 64% and 79%, respectively (more detailed diagram in Figure 5 of Publication II). Taking into account the losses in the process of oil shale mining as well as secondary energy consumed (i.e. electricity, steam and retorting gas), the efficiency decreased to 55% and 66% for the Kiviter and Galoter technologies, respectively.

The shale oil factories contribute remarkably to the total environmental pressure in Ida-Viru County. The pressure is important in the long-term perspective, when pollution and waste are accumulated in the surrounding environment. Pollution of air by hydrogen sulphide (H_2S) was about 0.03×10^{-6} t and 1.3×10^{-6} t per GJ of shale oil, by volatile organic compounds (VOCs) was 215.0×10^{-6} t and 115.010^{-6} t per GJ and by phenols 0.41×10^{-6} t and 0.83×10^{-6} t per GJ by Galoter and Kiviter technologies, respectively. However, because of the operation of shale oil producing factories, the concentration of H_2S, phenols and VOCs in the ambient air of towns where oil factories are located exceeds permissible levels by several times [76,77,78].

The hazardous waste disposal leads to the significant environmental pressure, burden of which is shifted to the shoulders of future generations. Three types of waste are generated in the process of shale oil production by two technologies: semi-coke, fusses (Kiviter technology) and black ash (Galoter technology). Semi-coke (i.e. solid residues), fusses (i.e. oil residues with high-ash fractions of oil shale, which contain polycyclic aromatic hydrocarbons (PAHs), phenols and other hazardous substances [68,123]) and ash (called black ash) generated in the process of shale oil production are classified as hazardous waste [9]. About 97.2×10^{-3} t of semi-coke and 2.3×10^{-3} t of fusses are generated per GJ energy of shale oil produced using Kiviter technology. However, taking into account the long-term history of shale oil production, to date in total about 96×10^{6} t of semi-coke is stored in an area of 2.5 km^2 located close to the oil factories. Semi-coke contains a wide range of environmentally hazardous compounds, including PAHs and water-soluble salts. The organic part of semi-coke, which comprises 9–16%, can cause self-ignition of semi-coke [88]. A large amount of leachate is formed in the process of precipitation infiltration. The pH of the leachate varies from 8.47 to 12.54. The polluted area of the groundwater is 2.5 km^2, and the pollution reaches a depth of 40–52 m [88]. The waste outcome (black ash) from the operation of Galoter technology was 101×10^{-3} t per GJ of oil shale, and this volume is transported for disposal into the ash fields of Narva PPs [96].

3.2.6. Implications and further elaboration for LCA

The extended LCA approach was applied in the present case study to examine the overall environmental pressures throughout the oil shale life cycle: mining, oil shale-based electricity generation and shale oil production. Carrying out careful and reliable inventory of the oil shale complex (based on the extended LCA) should be considered the most important part of the work. The broadening of LCA allowed to note and solve the limitations of LCA approach: the need to study the spatial aspects of the environmental pressure taking into account the geological and other natural peculiarities of the region where product manufacturing (e.g. the oil shale complex) is located (i.e. spatial aspect of LCA approach – to take the environmental sensitivity of a region into account) was emphasised along with the necessity to analyse indeed not only the short-term effects of the industrial processes but the processes from the start of the industrial exploitation as well, until the end in the (distant) future (i.e. the temporal aspect of LCA).

The result on environmental pressure occurred per GJ, annual and cumulative burden were discussed in detail throughout the main section. However, in order to understand the overall environmental pressure caused by the production and consumption of the oil shale resource, to focus and to clearly demonstrate needs in the broadening of LCA, several key aspects of the environmental pressures were discussed herein: the environmental pressure caused by production of one GJ of product (Table 1; the values of the parameters and figures characterizing processes and products are estimated averages) and the overall pressure on the environment due to the production.

Table 1. The environmental pressure associated with one GJ of oil shale-based products

Environmental pressure	Oil shale	Electricity and thermal energy[a]	Shale oil[c]
Energy "production" per m^2, GJ/m^2[b]	28	6.5	18, 22
Water consumption			
Pumped out, m^3/GJ	1.6		
Emissions into water bodies			
Sulphates (SO_4), 10^{-6}t/GJ	847.4		
Waste heat with cooling water, GJ/GJ		1.5	
Air pollution			
CO_2, 10^{-6} t/GJ		300	
Waste generation, 10^{-3}t/GJ	35	163[d]	97, 101[e]

[a] The focus was only centered on the environmental pressure of Narva PPs, because more than 90% of the total electricity in Estonia was generated in these PPs. The Narva PPs were the main consumers of oil shale – 97% of the total amount of oil shale used by the oil shale-based PPs was consumed by the Narva PPs in 2002.
[b] Calculated based on energy ratings of oil shale beds and efficiency of the production process (i.e., mining, electricity generation and shale oil production).
[c] The data are presented for the two technologies: Kiviter and Galoter technology, respectively.
[d] Defined as hazardous waste in accordance with [9].
[e] Defined as hazardous waste in accordance with [9]. The amount of fusses generated per GJ of shale oil is not reported in the table.

About 28 GJ (i.e. 3.5 t) of oil shale energy[7] is "mined out" of one m^2 (if the resource with an energy rating of 35 GJ/m^2 is being mined, about 20% of oil

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[7] A calorific value of kukersite (the scientific name of Estonian oil shale) seams (i.e., without limestone interlayers) is 12.5–13.5 GJ/t. A calorific value of oil shale consumed for electricity and thermal energy generation is 8.3–8.7 GJ/t; a calorific value of 8.5 GJ/t or 11.3–11.8 GJ/t (depending on technology) was consumed for shale oil production [67].

shale energy is “lost” in the mining and enrichment processes) (Table 1). About 70% of this energy is “lost” in the process of oil shale-based electricity generation; hence, to generate 6.5 GJ of electricity one m^2 of land is being “disturbed”. About 18 and 22 GJ (Kiviter and Galoter technology, respectively) is being “produced” from one m^2. Taking into account that the annual generation of electricity and thermal energy was 30.26×10^6 GJ in 2002, it was necessary to mine about 88.27×10^6 GJ; an annual production of 11.89×10^6 GJ of shale oil “needed” 25.96×10^6 of the oil shale resource to be mined. In this case, about 4 km^2 is transformed into “disturbed” land annually. To date, the whole period of oil shale extraction (more than 90 years, as over 1.6 billion tonnes have been extracted) has resulted in “transformation into disturbed mined-out land” of about 424 km^2, which comprised about 13% of Ida-Viru County’s territory in, where 79% is liable to subside in the coming decades.

Large mined out areas together with the hydrologically sensitive environment of oil shale deposits (i.e., oil shale beds are located deeper than the uppermost water body) places pressure on the region’s water resources. The interaction of the oil shale complex and the environment is described by two parameters in LCA approach (Table 1): about 1.6 m^3 of groundwater is withdrawn per GJ of oil shale resources in the mining process and about 850×10^{-6}t of sulphate per GJ of oil shale is pumped out into the surface water bodies. Nevertheless, these parameters do not properly demonstrate the pressure of the complex on water resources of the region’s; Since, the pressure occurs in two ways: (a) overexploitation of underground water resources (i.e., the amount of water pumped out from oil shale mines exceeded by a factor of five times the available resources of the GWB) and (b) pollution of the underground area (due to abandoned and flooded underground mines, with a total area of 220 km^2 with 170×10^6 m^3, the contamination with sulphates and other contaminants occurs quickly) and surface water (the content of sulphate in some of the lakes in the region has increased to 160–259 mg/l between 1946 and 2000, from 1–7 mg/l in 1937). Hence, there are needs for the future generations to look for new possibilities in technological and financial areas to provide the region with drinking water.

About 300×10^{-6} t CO_2 is emitted per GJ of electricity generated (Table 1), due to the high carbon content[8] in the oil shale and the 30% efficiency of electricity generation. The high CO_2 emissions from the oil shale-based energy sector (Estonia is a leading country in CO_2 emissions per monetary output among the energy sectors of the other EU countries) determines(d) high CO_2 emission intensity of the entire Estonian economy: Since the energy sector is the backbone of the country’s economy, high emissions associated with the electricity production is “distributed” among other sectors of the Estonian economy (via intermediate consumption) and affect the CO_2 emission intensities of other

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[8] The carbon content of oil shale is 27.85 kilograms of carbon per megajoule (kgC/MJ) [119].

goods and services (i.e., commodities) produced by the Estonian economy, which are comparably higher than the CO_2 emission intensities of commodities produced by other EU countries (see Chapter 3.3 and Publication III).

Four main types of waste are generated in the branches of the complex: waste rock, oil shale ash, semi-coke and fuses (Table 1). In general, due to the high content of mineral matter[9], about 30% of oil shale consumed (in terms of tonnage) is stored in landfills. The disposal of wastes requires areas of land and is accompanied by the self-ignition of these heaps (i.e., waste rock heaps) or contamination of underground water. To date, about 26 km^2 of the county's land is covered by wastes generated in the complex.

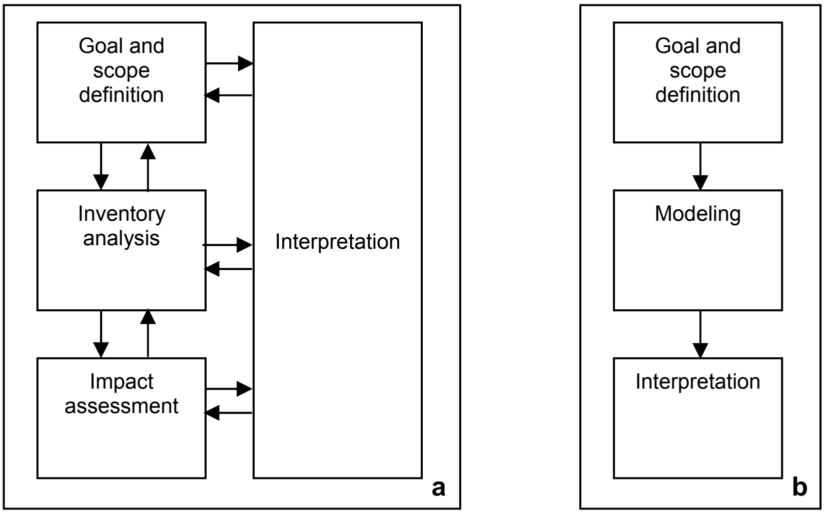

Figure 11. Algorithm of LCA approach established in the ISO standard (a) and developed for the SD concept (b) (modified from [50]).

Hence, the oil shale complex impacts the environment of Ida-Viru County, but plays an important role in the environment of Estonia at large. It is also important to note that understanding the overall environmental pressure associated with the shale oil production branch, as well as electricity and thermal energy generation branch, requires "embodying" the overall environmental pressure associated with production of the oil shale resource. These circumstances should be addressed in the overall environmental pressure associated with these branches that consume oil shale. In addition, Estonia exported(s) oil shale-based electricity and shale oil abroad. Hence, there is a necessity to address the overall environmental pressure embodied in these oil shale-based products and to "determine the responsibility" of consumers.

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[9] The kukersite contains organic, carbonate and terrigenous components. The latter two components constitute mineral matter, whereas organic matter content varies from 10 to 65% [67].

Hence, the present case study very clearly illustrate that, nowadays, there are needs in the extended LCA approach and in implementation of modelling in the framework of the approach, which can be developed by scientists in relevant areas with specific domain knowledge. Heijungs et al. [50] suggest the following framework for the further development of LCA, which includes a modelling phase (Figure 11), where the environmental sensitivity of a region and temporal dimensions are taken into account. In particular, these principles were employed in the present study, because the annual and cumulative burdens were examined based on a large number of scientific data, reports and articles available; the environmental modelling to determine the interaction of the oil shale extraction and the water complex of the region was applied as well. Nevertheless, the interpretation of the overall cumulative pressure (i.e. the evaluation of the cumulative pressure on the environment related to the unit of products) was not evaluated in the present study.

LCA approach is a labour-intensive and costly approach. Introduction and analysis of modelling into LCA approach would make the process even more time and labour-consuming. However, taking into account the temporal and spatial dimensions of environmental pressures would be a guarantee to achieving the objectives of the SD concept.

3.3. Production-based and consumption-based national greenhouse gas inventories of Estonia (Publication III)

3.3.1. Framework overview

Two types of national GHG inventories, which have been developed intensively during recent years, were compiled in the study. The production-based inventories are submitted annually to the UNFCCC, and they focus and define GHG emissions and removals occurring within the territory of a country due to production activities [58]. The consumption-based inventories [93] have their roots in the academic community and are becoming an increasingly important alternative accounting method for GHG emissions in the context of globalisation in the future. The inventory explicitly includes GHG emissions embodied in imported commodities and excludes GHG emissions associated with exported commodities. The results obtained by estimating GHG emissions using a consumption-based inventory reflect a fuller and more adjusted picture of overall GHG emissions in relation to the actual living standard (consumption level) of a country [Publication III].

Algebraically the basic difference of the two approaches is expressed in the equation (3) and visualised in Figure 4 [1]:

$$E_{DCd} = E_{DPd} - E_{EXdj} + E_{IMjd} , \tag{3}$$

where E_{DPd} represents the total CO_2eq emissions associated with the production of commodities within the boundaries of country *d*, E_{DCd} represents the total CO_2eq emissions associated with the consumption of commodities in country *d*, E_{EXdj} is the total CO_2eq emissions embodied in the commodities produced in country *d* and exported to countries 1...*j* and E_{IMjd} represents the total CO_2eq emissions embodied in the commodities produced in countries 1...*j* and imported to country *d*.

Three main gas emissions, CO_2, methane (CH_4) and nitrous oxide (N_2O), for the three main inventory sectors (energy, industrial processes and agriculture; energy- and non-energy-related emissions) were taken into account for Estonia for 2005 in the framework of production-based and consumption-based national GHG inventories For CH_4 and N_2O, emissions were converted to CO_2eq emissions.

The EEIO approach was used in the framework of consumption-based inventory: namely, the monetary standard IO tables [31,85] were extended with energy data [32,53,54,55,56] and afterwards with CO_2eq emissions, calculated using basic IPCC methods [60] (i.e. the quantities of primary and secondary fuels consumed, expressed in terajoule (TJ) terms, were multiplied by emission factors that quantify CO_2eq emissions per TJ). It allowed the direct CO_2eq emissions associated with the production of commodities by each sector of the (Estonian) economy to be estimated as well as allocation of the total energy consumed and CO_2eq emissions generated by a production-consumption system over different sectors for the production of commodities (i.e. intermediate consumption) and final use. In other words, rows showing energy consumption and emissions, which were added to the monetary IO table, enabled the estimation of a direct emission coefficient for each commodity. The domestic Leontief inverse matrix allowed to provide the simultaneous calculation of the total emission coefficient (i.e. direct and indirect intensities) of each commodity (see also Figure 3). Hence, the estimation of direct energy-related CO_2eq emissions and the total (direct and indirect) energy-related CO_2eq emissions associated with production of commodities allowed an understanding of the environmental interactions among the sectors, i.e. to trace which economic sector "received" CO_2eq emissions and, on the contrary, which sector "gave away" emissions.

On the whole, energy-related CO_2eq emission intensities were estimated for 42 categories of commodities, which were considered to be sufficient to provide an analysis of the emissions embodied in traded commodities [110]. The data on production, export and import of 42 commodities were grouped and recorded for the 15 main economic sectors. The total CO_2eq emission intensities were defined in tCO_2eq/1000€.

The estimation of energy-related CO_2eq emissions caused by the combustion of energy sources (i.e. the energy sector of national inventories submitted to the UNFCCC) associated with the bilateral trade and consumption of commodities was investigated based on the data obtained from the Eurostat [33] and the principles established using the EEBT approach.

Energy-related CO_2eq emissions occurring in the process of primary fuel production (extraction[10]; i.e. fugitive emissions) and those associated with consumption of the primary fuels were estimated based on the basic principles of the IPCC Guidelines [58] and the EEBT approach [Publication III]. The same methodological approaches were used to examine non-energy-related CO_2eq emissions resulting from manufacturing processes[11] and agricultural activities[12]. The data were obtained from [33,38,119, Publication III].

3.3.2. Emissions associated with production and consumption of commodities in Estonia

3.3.2.1. Energy sector

The total output of the Estonian economy was 24,255 million Euros (24,255×10^6€) in 2005. The total energy-related CO_2eq emissions ('CO_2eq emissions' in this sub-section) due to the combustion of primary and secondary fuels required to produce the commodities were 15,772 thousand tonnes of CO_2eq (15,772×10^3 tCO_2eq) in 2005 (Table 2). The allocation of direct (calculated based on the main rules of the IPCC) and the total (direct and indirect, calculated based on the EEIO approach) CO_2eq emissions among the sectors of Estonian economy are presented in Table 2.

The value of direct CO_2eq emissions resulting from the electricity and thermal energy generation industries, with an output value of 3% of the total monetary output of Estonia, calculated in the context of production-based inventory, was 74% from total direct energy-related CO_2eq emissions. The transport and commercial sectors, contributing 12% and 52% to the total output of the Estonian economy, respectively, to the total monetary value of produced commodities in the Estonian economy, emitted 14% and 2% from the total CO_2eq emissions in 2005, respectively.

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[10] Crude oil, natural gas and solid fuels.

[11] From manufacturing processes to produce cement, lime, glass, chemicals (i.e., nitric acid and ammonia) and iron and steel products.

[12] Emissions related to the production, bilateral trade and consumption of crops, living animals (i.e., cattle, swine, sheep, goats, horses and poultry) and livestock-related products (i.e., beef, pork, mutton, poultry, goat and horse meat and cow milk).

Table 2. Production of commodities by sector of the Estonian economy in 2005 and associated energy-related emissions calculated based on production- and consumption-based inventory approaches

Nr	Sector of the economy[a]	Output, 10^6€	Emissions related to production of commodities in different sectors, 10^3tCO$_2$eq		
			Direct emissions	Total (direct and indirect) emissions	Differences between values
1	Fuel extraction industry	137	169	72	98
2	Coke and refined petroleum products industry	75	0.0	82	-82
3	Electrical and thermal energy generation industry	676	11,617	5,092	6,525
4	Iron and steel industry	247	1.3	104	-103
5	Non-ferrous metal industry	498	1.1	93	-92
6	Chemical industry	566	141	484	-343
7	Non-metallic mineral products industry	303	428	278	150
8	Ore extraction industry	48	24	15	9
9	Food, drink and tobacco industry	1,030	135	927	-792
10	Textile, leather and clothing industry	561	41	364	-323
11	Wood and wood products, paper and printing industry	1,390	39	719	-680
12	Engineering and other metal industry	2,453	47	670	-623
13	Agriculture, hunting, forestry and fishing	828	232	240	-8
14	Transport	2,861	2,282	1,935	347
15	Commercial sector	12,548	285	4,368	-4,083
	Households		328[b]	328[b]	
	Total	24,225	15,772	15,772	

[a] The energy-related emission intensities of the 15 main sectors were estimated as follows: (1) the energy-related emissions that occur in the process of producing commodities were summed in accordance with the sector classification presented in [Publication III]; (2) the monetary output of each sector was summed up based on the same rules, i.e. monetary output related to commodity produced was summed up in accordance with the sector classification.

[b] Direct energy-related CO$_2$eq emissions due to the combustion of primary and secondary fuels by households in Estonia in 2005.

Table 3. Direct energy-related emission intensities of the main economic sectors of Estonia and several EU27 countries in 2005, $tCO_2eq/1000€$

Sector[a,b]	Estonia (EE)	Austria (AT)	Czech Republic (CZ)	Germany (DE)	Finland (FI)	France (FR)	Lithuania (LT)	Latvia (LV)	Poland (PL)	Sweden (SE)
1	1.24	1.47	0.09	0.31	0.15	0.00	0.44	0.00	0.35	0.00
2	0.00	1.12	0.54	0.53	0.41	0.35	1.82	0.00	0.89	0.29
3	17.18	0.98	6.87	4.06	5.10	0.73	2.31	4.91	9.76	0.79
4	0.01	0.90	1.88	0.73	0.70	0.59	0.19	2.07	1.27	0.56
5	0.00	0.02	0.02	0.03	0.01	0.02	0.00	0.03	0.09	0.02
6	0.25	0.09	0.41	0.08	0.13	0.11	0.03	0.11	0.28	0.07
7	1.41	0.32	0.50	0.41	0.37	0.40	1.50	2.70	0.96	0.46
8	0.50	0.13	0.16	0.13	0.05	0.09	0.21	0.30	0.15	0.20
9	0.13	0.06	0.12	0.05	0.04	0.06	0.13	0.36	0.16	0.05
10	0.07	0.05	0.10	0.04	0.08	0.03	0.09	0.22	0.08	0.06
11	0.03	0.10	0.09	0.07	0.17	0.05	0.00	0.01	0.11	0.07
12	0.02	0.01	0.03	0.01	0.00	0.02	0.04	0.10	0.03	0.01
13	0.28	0.14	0.24	0.13	0.24	0.16	0.11	0.31	0.61	0.17
14	0.80	1.12	1.09	0.95	0.74	1.06	1.32	1.42	1.29	0.60
15	0.02	0.01	0.03	0.02	0.01	0.01	0.02	0.03	0.03	0.01

[a] The direct energy-related emission intensities of the 15 main sectors were estimated as follows: (1) the energy-related emissions that occur in the process of producing commodities were summed in accordance with the sector classification presented in [Publication III]; (2) the monetary output of each commodity was summed up based on the same rules; (3) the direct energy-related emissions summed for each economic sector were divided by the total output of each sector.

[b] The list of sectors is presented in Table 2.

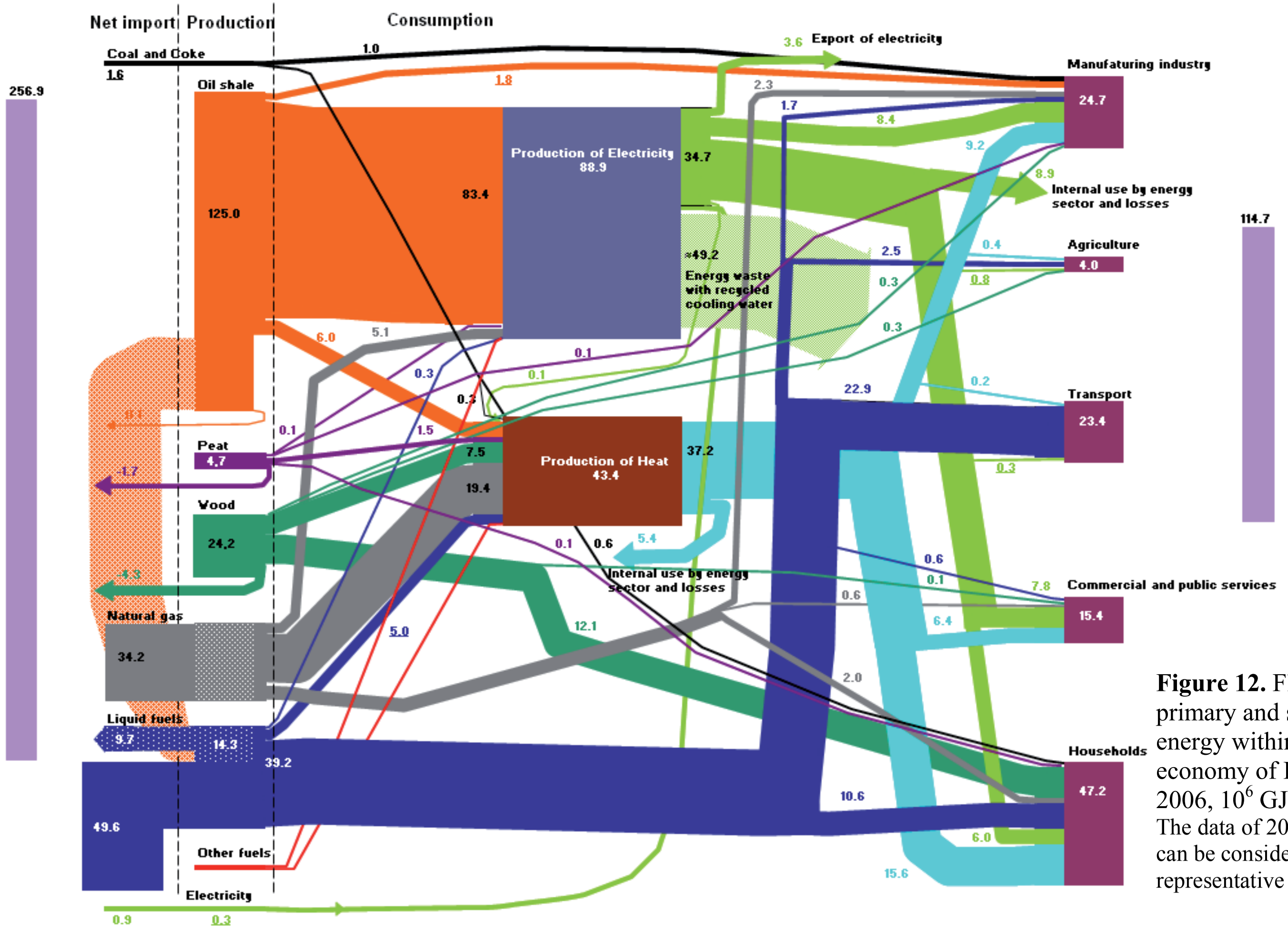

Figure 12. Flows of primary and secondary energy within the economy of Estonia in 2006, 10^6 GJ.
The data of 2006 presented can be considered as representative [40].

The Estonian electricity and thermal energy generation industry is one of the most CO_2eq (direct) emission-intensive energy sectors of the countries of the European Union (EU27; Table 3) due to the low efficiency of electricity and thermal energy generation and high content of carbon in oil shale resources (Figure 12) [Publication II]. The direct emission intensities of commodities produced by other economic sectors of Estonia are in line and comparable with the corresponding direct emission intensities produced in the other EU27 countries (Table 3).

The application of the EEIO approach demonstrated clearly the extent of "the distribution" of CO_2eq emissions due to intermediate consumption of commodities within the Estonian economy (Table 2). The significant "distribution" of CO_2eq emissions (more than 50% in absolute value) from the electricity and thermal energy generation industry to the other sectors of the Estonian economy (i.e. mainly to commodities in the food, drink and tobacco industry, textile and clothing industry, wood and paper industry, engineering and other metal industry) is taking place.

Table 4. Total energy-related emission intensities of the main economic sectors of Estonia and Estonia's main trade partners in 2005, tCO_2eq/1000€

Nr	Estonia (EE)	Finland (FI)	Germany (DE)	Lithuania (LT)	Latvia (LV)	Sweden (SE)	Russia (RU)[b]
1	0.52	0.06	0.32	0.11	0.27	0.02	6.55
2	1.10	0.31	0.37	1.82	0.08	0.24	2.27
3	7.53	1.22	2.06	0.88	3.36	0.35	12.82
4	0.42	0.67	0.67	0.24	2.02	0.48	4.86
5	0.19	0.09	0.12	0.05	0.16	0.05	1.21[c]
6	0.86	0.22	0.18	0.17	0.30	0.11	17.42
7	0.92	0.20	0.29	0.90	1.17	0.23	1.06
8	0.31	0.06	0.11	0.08	0.13	0.12	6.60
9	0.90	0.23	0.24	0.41	0.41	0.14	2.48
10	0.65	0.17	0.20	0.20	0.37	0.14	4.41
11	0.52	0.38	0.15	0.08	0.31	0.14	3.04
12	0.27	0.10	0.13	0.16	0.32	0.06	3.85
13	0.29	0.11	0.13	0.13	0.33	0.04	1.96
14	0.68	0.32	0.46	1.08	1.21	0.31	4.41
15	0.35	0.13	0.07	0.12	0.16	0.04	3.47

[a] The total energy-related emission intensities of the 15 main sectors were estimated as follows: (1) the energy-related emissions that occur in the process of producing commodities were summed up in accordance with the sector classification presented in [Publication III]; (2) the monetary output of each commodity was summed up based on the same rules; (3) the total energy-related emissions summed up for each economic sector were divided by the total output of each sector.

[b] The data for 2000.

[c] The value of the Chinese non-ferrous metal industry was used in the estimates.

[d] The list of sectors is presented in Table 2.

The “distribution” of CO_2eq emissions via intermediate consumption of commodities influenced the values of the total (direct and indirect) emission intensities of all commodities produced in Estonia. The data in Table 4 illustrate the fact that Estonia is a leader among the other EU27 countries in CO_2eq values of the total emission intensities of commodities produced.

Total CO_2eq emissions embodied in the export of the commodities were $3{,}703\times10^3$ tCO_2eq in 2005 (Table 5). Of the total CO_2eq emissions “exported”, those embodied in the transport sector, engineering and in the other metal industry, wood and printing industry and chemical industry commodities were dominant. Finland (21% of the total CO_2eq embodied in the export), Latvia (15%), Sweden (9%) and Russia (10%) were the main destinations for the commodities associated with these CO_2eq emissions (Table 7). In general, Estonia’s export of CO_2eq embodied emissions went to countries with total CO_2eq emission intensities lower than that of Estonia, with the exception of Russia and several sectors of Latvia (Table 4).

Table 5. Energy-related emissions associated with import, export and consumption of commodities by sectors of the Estonian economy in 2005, 10^3 tCO_2eq

Nr	Sector of the economy[a]	Import	Export	Consumption
1	Fuel extraction industry	263	12	322
2	Coke and refined petroleum products industry	769	60	792
3	Electrical and thermal energy generation industry	8	307	4,794
4	Iron and steel industry	745	108	741
5	Non-ferrous metal industry	65	39	119
6	Chemical industry	1,780	397	1,867
7	Non-metallic mineral products industry	69	89	258
8	Ore extraction industry	25	2	38
9	Food, drink and tobacco industry	240	329	838
10	Textile, leather and clothing industry	284	356	292
11	Wood and wood products, paper and printing industry	663	439	942
12	Engineering and other metal industry	1,131	544	1,257
13	Agriculture, hunting, forestry and fishing	90	42	288
14	Transport	406	726	1,615
15	Commercial sector	312	253	4,427
	Households			328[b]
	Total	6,850	3,703	18,919

[a] The data on production, export and import of 42 commodities (in 10^6€ and 10^3 tCO_2eq) were grouped and recorded for the 15 main economic sectors. See also [Publication III] for the classification of the sectors and commodities produced by each sector.

[b] Direct energy-related CO_2eq emissions due to the combustion of primary and secondary fuels by households in Estonia in 2005.

Total CO_2eq emissions embodied in the commodities imported to Estonia were 6,850×10^3 tCO_2eq in 2005 (Table 5). Of these emissions, the major contribution was provided by chemical industry goods (26%), engineering and other metal industry products (17%), coke and petroleum products and iron and steel industry commodities (each sector contributed 11% to the total CO_2eq emissions embodied in imports) and goods of the wood and printing industry (10%). Russia exported the most embodied emissions to Estonia (approximately 50%). These CO_2eq emissions were embodied in products of the chemical industry (1,310×10^3 tCO_2eq), the wood and printing industry (576×10^3 tCO_2eq) and the coke and refined petroleum industry (510×10^3 tCO_2eq).

Total CO_2eq emissions associated with the consumption of commodities in Estonia were 18,919×10^3 tCO_2eq in 2005 (Table 5). This value is approximately 20% higher than that for CO_2eq emissions associated with production.

Fugitive emissions

Total energy-related fugitive CO_2eq emissions ('CO_2eq fugitive emissions') that occurred in the process of primary energy extraction amounted to 15×10^3 tCO_2eq (Table 6) in Estonia in 2005. The main source-activity of the total fugitive CO_2eq emissions occurred due to the extraction of peat energy. The production of oil shale was not a source of the release of fugitive emissions [119].

The export of primary energy from Estonia was associated with 0.4×10^3 tCO_2eq of fugitive emissions (Table 6). More than 75×10^3 tCO_2eq of fugitive emissions were embodied in the primary fuels imported to Estonia in 2005. Of total CO_2eq emissions, approximately 10% of the emissions were embodied in imported solid fuels (specifically coal; the import of oil shale was not associated with the import of embodied emissions); the remainder of the CO_2eq fugitive emissions were associated with imported natural gas.

Table 6. Energy-related and non-energy-related emissions associated with production, bilateral trade and consumption of primary fuel energy, manufacturing products and agriculture-related products in 2005, 10^3 tCO_2eq

Sector	Import	Production	Export	Consumption
Primary fuels	75	15	0.4	89
Manufacturing product	29	677	301	406
Agriculture-related product	320	814	128	1,008

Total fugitive CO_2eq emissions associated with the consumption of primary energy in Estonia were 89×10^3 tCO_2eq in 2005, approximately six-fold higher than the emissions associated with its production (Table 6). However, the absolute values of the fugitive emissions involved were low.

3.3.2.2. Industrial processes

Total non-energy-related CO_2eq emissions (‘CO_2eq emissions’ in this sub-section) associated with industrial production were 677×10^3 tCO_2eq in 2005 (Table 6). The majority of CO_2eq emissions released was contributed to by the production of cement and lime products (59%), and the rest to the products of chemical industry.

The total export of manufacturing products by Estonia was associated with emissions of 301×10^3 tCO_2eq in 2005. Estonia’s CO_2eq emissions were primarily embodied in products exported to Latvia (70% of the total CO_2eq emissions associated with exports), Finland (11%) and Russia (19%) (Tables 6,7). Of the total CO_2eq emissions embodied in exports to Latvia, approximately 40% were associated with cement and lime products and 60% with ammonia. Of the CO_2eq emissions embodied in exports to Finland, 98% were contributed by emissions embodied in cement and lime products. Of Estonia’s exports of manufacturing products to Russia, 100% were associated with CO_2eq emissions embodied in cement and lime products.

Total CO_2eq emissions associated with imports to Estonia were 29×10^3 tCO_2eq in 2005. The main trade partners in embodied CO_2eq emissions were Finland and Sweden (Tables 6,7). Approximately 41% of the total CO_2eq emissions embodied in imports from Finland were in cement and lime products, and 59% were “imported” with glass products. Approximately 95% of CO_2eq emissions embodied in Swedish imports were in cement and lime products, with the rest in glass products.

Total CO_2eq emissions associated with the consumption of cement, lime, glass and chemical products were 406×10^3 tCO_2eq (Table 6), or 40% less than the total CO_2eq emissions associated with their production.

3.3.2.3. Agriculture

Total non-energy-related CO_2eq emissions (‘CO_2eq emissions’ in this sub-section) associated with the production of agricultural products were 814×10^3 tCO_2eq in 2005 (Table 6).

Total CO_2eq emissions embodied in Estonian exports of agricultural products were 128×10^3 tCO_2eq in 2005; more than 20% of the embodied emissions were exported with livestock, 34% were exported with pork and 14% with beef, and the emissions associated with the export of cow milk contributed approximately 20% of the total emissions associated with exports of agriculture-related products. The destination countries of the CO_2eq emissions embodied in Estonia’s exports were Latvia, Lithuania and Poland (Table 7).

Table 7. Energy-related and non-energy-related emissions associated with the import and export of commodities to and from Estonia by trade partners in 2005, in 10^3 tCO_2eq

Trade partner of Estonia	Emissions embodied in bilateral trade involving…									
	goods and services[a]		primary fuels		manufacturing products		agricultural products		Total	
	Import	Export	Import	Export	Import	Export	Import	Export	Import	Export
Belgium (BE)	28	44	-	-	1	-	15	0	44	44
Finland (FI)	315	777	-	0.4	16	34	70	8	401	820
Germany (DE)	203	199	-	-	1	0	38	8	242	207
Denmark (DK)	24	107	-	-	0	0	108	1	132	108
Lithuania (LT)	200	206	-	-	0	1	14	27	214	234
Latvia (LV)	215	548	-	-	0	209	6	48	221	805
Netherlands (NL)	57	64	-	-	0	0	10	2	67	67
Poland (PL)	166	36	-	-	2	0	19	18	187	54
Sweden (SE)	75	320	-	-	5	0	10	5	90	325
United Kingdom (UK)	47	163	-	-	0	0	1	0	48	163
Other EU27 countries	180	174	-	-	2	0	25	6	207	180
China (CN)	338	10	-	-	0	0	0	-	338	10
Russia (RU)	3,402	374	75	-	1	56	0	3	3,478	433
United States (US)	43	133	-	-	0	0	0	0	43	133
Other non-EU27 countries	1,557	548	-	-	2	0	3	1	1,562	549
Total	6,850	3,703	75	0.4	29	301	320	128	7,274	4,132

[a] Energy-related CO_2eq emissions embodied in Estonia's bilateral trade of 42 commodities.

Of the total CO_2eq emissions embodied in Estonia's exports to Latvia, more than 50% were associated with meat (i.e. beef and pork) and approximately 30% were related to livestock exports. Of the CO_2eq emissions embodied in exports to Lithuania, 85% were embodied in meat and 10% were associated with milk exports. Of Estonia's exports to Poland, more than 85% were associated with livestock exports and more than 10% were associated with meat (Table 7).

Total CO_2eq emissions embodied in imports were 320×10^3 tCO_2eq in 2005 (Table 7); approximately 70% of the total emissions were "imported" with pork and approximately 20% with beef. The majority of CO_2eq emissions embodied in agriculture-related products were imported from Denmark (34% of the total CO_2eq emissions embodied in the imports), Finland (22%) and Germany (12%). Of the CO_2eq emissions embodied in exports from Denmark and Finland, 100% were associated with meat. Germany's agricultural exports to Estonia consisted of approximately 65% emissions embodied in meat and more than 25% emissions associated with soybean imports (Table 7).

In total, $1{,}008\times10^3$ tCO_2eq were associated with the consumption of agriculture-related products (Table 6). Emissions related to agricultural consumption exceeded those related to agricultural production by 24% in 2005.

3.3.2.4. Total CO_2eq emissions associated with the production and consumption of commodities

Total CO_2eq emissions (i.e. energy-related and non-energy-related) associated with the production of commodities in Estonia were $17{,}278\times10^3$t in 2005; the majority of these emissions occurred in the energy sector. Non-energy-related CO_2eq emissions associated with agricultural products made up 5% of the total, and 4% of the non-energy-related emissions occurred in manufacturing.

Total CO_2eq emissions (energy-related and non-energy-related) associated with the consumption of commodities were $20{,}420\times10^3$t. The latter value exceeded the emissions associated with production by 18%. The percentage structure by sector of the CO_2eq emissions associated with consumption was nearly the same as for production-based emissions.

Total CO_2eq emissions embodied in the export of commodities from Estonia were $4{,}132\times10^3$ tCO_2eq in 2005. Total CO_2eq emissions embodied in the import of commodities during the same period were equal to $7{,}274\times10^3$ tCO_2eq. Estonia "net imported" CO_2eq emissions embodied in commodities traded primarily from Russia, China, Kazakhstan, Ukraine and Belarus and "net exported" to the EU27 countries, the United States, Norway and Switzerland in 2005.

Among the EU27 countries, the main "net importers" of Estonia's CO_2eq emissions were the neighbouring countries of Latvia, Finland, Sweden and Lithuania. The main "net exporters" of CO_2eq emissions were Poland and Germany (Table 7). The emission balances of the Netherlands and Belgium, due to bilateral trade with Estonia, were close to zero, because, although these countries were net importers of energy-related CO_2eq emissions, they net exported non-energy-related CO_2eq emissions in agricultural products. In a similar manner, an emission balance due to the Estonia's bilateral trade with Denmark; Denmark net imported energy-related CO_2eq emissions from Estonia (83×10^3 tCO_2eq) but net exported non-energy-related CO_2eq emissions associated with agricultural products (107×10^3 tCO_2eq) [Publication III].

3.3.3. Implications and further elaboration for the EEIO

The EEIO approach was employed to perform two types of GHG national inventories for Estonia – production-based and consumption-based. To date, Estonia has been one of the less studied countries in this area. The GHG emissions associated with the production and consumption of commodities in Estonia were recorded only in the framework of global-scale studies [3,6,95,94,102]. No detailed data on GHG emissions embodied in commodities imported and exported have been presented and no sector level analysis of differences in GHG emissions according to the production-based and consumption-based inventories had been performed. However, nowadays in the era of combating climate change, it is reasonable to assume that further rational climate policies should be developed based on sound knowledge and a sound understanding of the objective situation [Publication III].

The use of the EEIO approach allowed direct GHG emissions associated with production of commodities as well as the total (direct and indirect) emissions to be examined and determination of how the emission-efficiency of each sector influences the emission-efficiency of other sectors.

In general, the EEIO method is considered to be an advanced and comprehensive tool to perform consumption-based GHG inventories. The large datasets of the IO tables developed as well as the availability of data on energy consumption and international trade facilitated significantly attainment of the objective picture. The choice of calculation approach between the EEBT and the MRIO primarily determines the differences in the value of the total GHG emissions associated with consumption because of the different ways these two approaches treat data on imported commodities in intermediate production. However, both approaches are legitimate and are used to pursue different study objectives. Nevertheless, the consumption-based GHG inventories, completed earlier to examine only energy-related GHG emissions, other types of GHG emissions, i.e. non-energy-related, were not considered. The present case study focused also on the estimation of non-energy-related GHG emissions associated with production and consumption of commodities. Attention was paid to non-energy-related GHG emissions, which played a key role in determination of the CO_2eq emission balances associated with the trade between Estonia and several countries. For example, the energy-related CO_2eq emission balance between Estonia and Denmark, and the Netherlands, was achieved thanks to the non-energy-related CO_2eq emissions embodied in agricultural and manufacturing products bilaterally traded with Estonia by these countries.

Nevertheless, a wide range of challenges/questions shall be solved before detailed, comprehensive and accurate consumption-based GHG inventories, addressing all challenges of globalisation, could be used as a supplemental tool in determining global policy on climate change. For example, GHG emissions from the land use and land use change (LULUCF) and waste sectors should certainly be included in the analysis of the GHG emissions. The consideration of non-energy-related CO_2eq emissions associated with the LULUCF sector could make a remarkable difference in the calculated balance of GHG emissions between production-based and consumption-based GHG inventories. The next case study will illustrate it based on the example of soybean imports to Austria [Publication I]. The non-energy-related GHG emissions associated with the waste sector would contribute presumably less to the difference between the two GHG inventories than inclusion of the LULUCF sector. GHG emissions released from the waste sector make up approximately 2–10% of the total GHG emissions of a country in production-based inventories [119]. However, the data on emissions from waste storage should be included to guarantee the completeness of the inventory. Using both the EEBT and MRIO approaches in compiling the inventories seems reasonable. This would allow more transparent analysis of GHG emissions associated with bilateral trade balances.

The enhancement of the approach developed for consumption-based inventories requires compiling large datasets and the method is time-consuming and cost-intensive. However, the completion of consumption-based GHG inventories is a valuable tool in the development of policies towards a sustainable society.

3.4. International trade and Austria’s livestock system (Publication I)

3.4.1. Framework overview

Austria’s livestock production system, including Austria’s bilateral trade with livestock products and feedstuffs, was examined using the FCA approach in this case study.

GHG emissions associated with production and consumption were aggregated into three main categories: (a) livestock biomass production; (b) fossil fuel consumption in the production process; and (c) land use activities outside Austria’s national borders. In detail, the following CO_2 and CH_4 emissions were investigated: emissions related to Austria’s livestock biomass production (cattle and pigs), namely, emissions resulting from enteric fermentation (recalculated to carbon, C_CH_4) and manure management (C_CH_4); emissions from production processes (C_CO_2); and emissions from transportation of animal products (C_CO_2) and product (beef and pork, milk) manufacturing (C_CO_2). The emissions are visualised in Figure 13.

The same categories of carbon emissions were estimated in the context of Austria's consumption of livestock-related products. The principle described in the formula (3)[13] was used to estimate Austria's emissions associated with consumption.

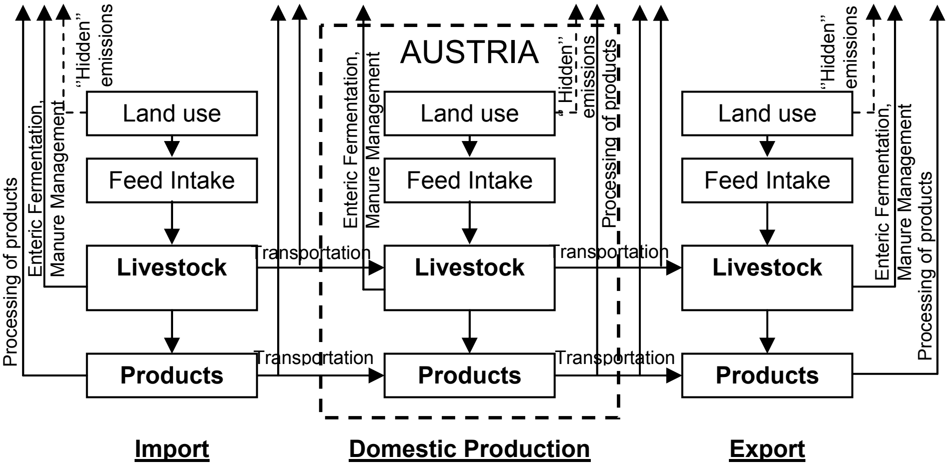

Figure 13. System description of carbon flows related to Austria's domestic production and its bilateral trade of living animals and animal products.

Carbon emissions from land use (direct and indirect) change due to animal feed production (C_CO_2) were accounted as "hidden" emissions (Figure 13). Carbon input via feed intake by animals and land requirements were estimated to evaluate biomass demand and land needed for the production of livestock feedstuffs. CO_2 emissions (flows) were calculated in units of thousand tonnes of carbon per year (ktC/yr), and land area used for animal feed production was estimated in units of thousand hectares (kha) [Publication I]. Soybean products and GHG emissions associated with them, imported directly and indirectly to Austria from Argentina and Brazil, were under detailed consideration in the framework of the present study. It should be reminded that soybean production in Brazil and Argentina is one of the driving forces for deforestation in these countries [39,46,79,80,82,124].

To examine carbon emissions embodied in the soybean products imported directly and indirectly to Austria, a material flow-based algorithm was developed (see Figure 14). The adjustment of trade data was based on the assumption that exports of the countries of origin consist of domestically produced and imported soybeans, which is described by the domestic material input (DMI, the sum of domestically produced and imported products).

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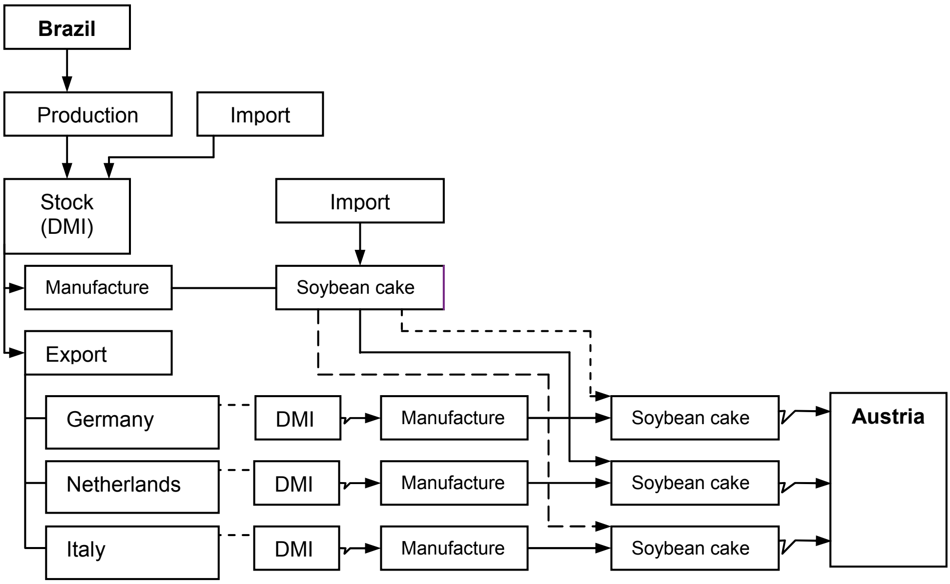
[13] The formula was explained on p. 41.

Two cases were applied, based on simple assumptions, to the estimated deforestation rate due to soybean production exported to Austria: (a) soybeans directly (or indirectly) imported from Brazil are produced on directly and indirectly deforested land; and (b) about 10% of the soybeans produced in Argentina and imported to Austria are from non-traditional agricultural areas that had been deforested. "Hidden" carbon emissions embedded in soybean products fed to Austrian livestock are investigated under the simplifying assumption that equal pieces of land were deforested over a 20-year period in Brazil and a 10-year period in Argentina.



DMI – Domestic Material Input

Figure 14. Algorithm to handle soybean and soybean cake imported from Brazil as a producing country through Germany, the Netherlands and Italy as third countries. (The same algorithm is used for estimating the amounts of soybean and soybean cake imported from Argentina).

The study referred to the year 2000. Data on domestic production and Austria's bilateral trade with livestock products (living animals, meat, milk and milk products) were obtained from the FAO databases [36,37]. The FAO databases contain data by country of origin/final destination and traded product. They allow the trade network structure of Austria to be traced. The emission factors on animal enteric fermentation and manure management systems and emissions from product processing and transportation were used from the IPCC Guidelines and GEMIS database [41,58,61,Publication I].

3.4.2. Carbon flows related to production and consumption of living livestock and livestock-related products

Carbon emissions from domestic livestock production, total 922 ktC/yr (Figure 15), consisted of: (1) 723 ktC/yr (78%) from production; (2) 122 ktC/yr (13%) from enteric fermentation; and (3) 76 ktC/yr (8%) from manure management. About 83% of the total carbon emissions resulted from husbandry, i.e. from raising cattle and manufacturing dairy products (milk). Carbon emissions from producing pig biomass (live animals and products) amounted to 17% [Publication I].

Table 8. Austria's domestic production, import and export of livestock biomass in 2000

	Import	Domestic Production	Export	Balance
Living animals, [heads/yr]				
…cattle	34 367	2 171 681	144 593	2 061 455
…pigs	283 394	3 430 995	26 188	3 688 201
Cattle meat, [t/yr]	14 790	203 489	70 034	148 245
Pig meat, [t/yr]	108 467	620 404	134 456	594 415
Milk, [t/yr]	762 525	3 364 290	1 332 194	2 794 621

Austria was a net-exporter of living animals and livestock-related products in 2000, with the exception of trade with living pigs (Table 8). Austria mainly traded with countries of Western and Eastern Europe.

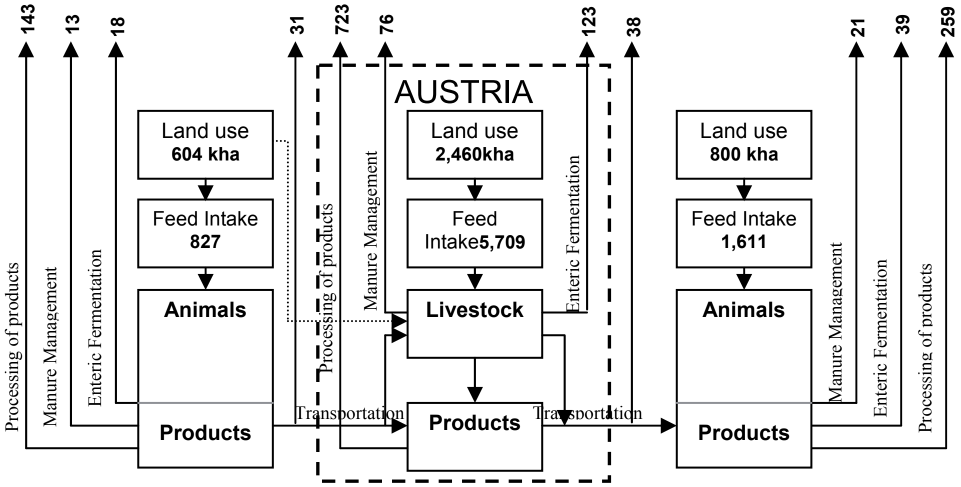


Figure 15. Total carbon emissions from domestic production, import and export of livestock biomass (cattle, pigs) in 2000, in ktC.

Carbon “embodied” in imports related to Austria’s livestock sector amounted to 205 ktC (Figure 15). Total emissions resulted from the following sources: 143 ktC (70%) from fuel combustion during production; 31 ktC (15%) from transportation of products to Austria; and 31 ktC (15%) from enteric fermentation and manure management.

Carbon “embodied” in livestock biomass exported from Austria was about 358 ktC (Figure 15), whereas more than 259 ktC (72%) was emitted from livestock product manufacturing, 38 ktC (11%) was emitted from livestock biomass transportation and 61 ktC (17%) from enteric fermentation and manure management [Publication I].

Austria’s carbon emissions related to domestic consumption of livestock products were only 768 ktC. This means that Austria’s emissions due to domestic consumption were about 153 ktC less than its carbon emissions associated with domestic production (Figure 15).

3.4.3. Carbon flows related to production and consumption of feedstuffs

On average, 0.5 ha was used in order to produce 1 tonne of carbon consumed by Austrian livestock: the total land required for Austria’s livestock was about 2,460 kha, and the total feed intake about 5,709 ktC. An equivalent of 800 kha was exported embodied in living livestock and livestock-related products from Austria. On average, 0.7 ha was required for producing 1 tonne of carbon contained in feedstock (market and non-market feed and grazing) consumed by animals (live animals and products) exported to Austria. The total land required was about 604 kha and the feed intake about 76 ktC [Publication I]. Carbon emissions due to land use to produce crops fed to the livestock were assumed to not have occurred, in accordance with the 1996 IPCC Guidelines [58].

Nevertheless, the picture changes if land-use related carbon emissions due to soybean production are taken into account. In general, soybean products were the largest fraction (64%) of feedstock imported to Austria[14] in the year 2000 (equivalent to 11% of Austria’s total imports) [36]. Austria’s domestic production of soybean was negligible (3.6% of total soybean consumption in 2000), indicating Austria’s dependence on imports of soybean products, which increased 39-fold between 1961 and 2004 (from 14.6 thousand tonnes (14.6×10^3) in 1961 to 387×10^3 tonnes in 1980 to 577×10^3 tonnes in 2003) [37, Publication I].

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[14] Other feedstock imported to Austria (e.g. cereals and co-products) and feedstuffs exported from Austria (e.g. rapeseed cake) were assumed to be carbon-neutral during cultivation and production.

Table 9. Total amount of soybeans harvested for consumption in Austria and land area required for soybean cultivation

Country of origin of soybean cultivation	Soybean "indirect" import to Austria, kt/yr	Land required for cultivation, kha	Area deforested directly (d) and indirectly (i) for soybean production, kha (% of the total cultivated areas)
Argentina	172.800	73.846	7.385 (d: 10%)
Brazil	207.709	86.546	34.618 (i: 40%)
the USA	109.227	42.667	
Total	489.736	203.059	42.003

Austria's soybean import mainly originates from Germany, Italy and the Netherlands [37]. But their production of soybeans is negligible in the global context and, with the exception of Italy, not even sufficient to cover the amount transported to Austria. However, these countries imported soybean products mainly from the US, Brazil and Argentina, where the last two countries are known as countries with high deforestation rates [39,46,79,80,82,124]. Due to the algorithm developed and presented in Figure 14 that about 490 kt soybean products (fresh matter) imported to Austria in 2000 required an area of 203 kha, more than 381 kt (75% of Austria's total soybeans imports) were cultivated in Brazil and Argentina on an area of 160.4 kha, where about 42 kha of land had directly and indirectly been deforested (Table 9) [Publication I]. The process was a driving force for emission from deforestation in Brazil and Argentina of 277.4 ktC in 2000. Taking into account assumptions of the extreme case, about 5,028.2 ktC was emitted due to deforestation in Brazil and Argentina for production of soybean exports to Austria.

3.4.4. Total carbon emissions associated with production and consumption

Direct carbon emissions embodied in imports related to Austria's livestock sector amounted to 205 ktC. Direct carbon emissions "embodied" in livestock biomass exported from Austria were about 358 ktC. Considering trade, Austria's carbon emissions related to domestic consumption of livestock products were only 768 ktC. This means that Austria's emissions due to domestic consumption were about 153 ktC less than its carbon emissions associated with domestic production (Table 10).

Taking into account "hidden" emissions embodied in feedstuffs (soybeans) imported to Austria, Austria's balance of carbon emissions estimated in accordance with the consumption accounting principle would increase to about 1,045 ktC, surpassing Austria's emissions calculated according to the production principle by about 1.13-fold (Table 10).

Table 10. Carbon embodied in animal products traded with Austria in 2000, in ktC

	Carbon "embodied" in Import	Emissions related to Production	Carbon "embodied" in Export	Emissions related to Consumption
Carbon embodied in livestock biomass	204.756	921.761	358.137	768.380
Carbon embodied in livestock feed imported to Austria [area deforested, ha/yr]	277.4 [2,402]			1,045.8

3.4.5. Implications and further elaboration for the FCA

The FCA approach is considered to be a sound and comprehensive tool used to address all GHG emissions associated with the production of a product, process or activity. The FCA approach was developed based on the main principles of LCA, but the focus was only on GHG emissions related to production.

The approach combines the estimations of different types of GHG emissions: energy-related (i.e. due to fuel combustion) and those related to non-energy-related activities (i.e. agricultural activities, industrial processes, waste and direct land use change), and allows the contribution of each of them to the total quantity of GHG emissions to be taken into account.

The present third case study is a good example of the application of FCA approach in the agricultural sector based on the example of Austria's husbandry sector. Carbon emissions associated with production and consumption were evaluated in the study. The indirect GHG emissions from land use changes by taking into account the temporal aspect of changes in land use (i.e. a 20-year period) were estimated.

The results of the case study completed illustrated all carbon emissions related to the sector and determined the contribution of each category of emissions to the total value of carbon emissions. The results also demonstrated the scale of GHG emissions occurring due to indirect changes in land use. The carbon balance of Austria's husbandry sector significantly changed after taking into account the emissions associated with land use changes. Such type of analysis is especially important in the context of products of agricultural sectors, e.g. crops or livestock-related products, which are, in most cases, considered to be the driving force for deforestation. Undoubtedly, in order to account for emissions occurring due to indirect changes in land use, additional modelling (e.g. based on MFA approach) and large datasets would be required, which illustrate the direct and indirect relations between a certain product's production and changes in land use (i.e. deforestation). The accounting would become labour and cost-intensive. However, the analysis, first of all, could be considered to be an important tool for acting reasonably in the framework of the SD concept. It would help to understand all the driving forces for deforestation and minimise them and to reduce GHG emissions in order to reduce impacts on the climate system.

4. CONCLUSIONS

4.1. Summary of research findings

The general goal of the dissertation was to examine and document the interactions of 'economic activities and the environment' on the national and international levels. The LCA, EEIO and FCA accounting approaches, developed under the SD framework, were extended and enhanced for this purpose.

In general, the results of the present dissertation could be summarised shortly as follows:

- The LCA of the Estonian oil shale complex was carried out. It allowed to document and analyse comprehensively the spatial and temporal aspects of the environmental pressure of the complex. The environmental pressures caused by oil shale mining industry, electricity and thermal energy generation branch and shale oil production industry were evaluated;
- The EEIO approach was used to estimate direct and the total (direct and indirect) CO_2eq emission intensities of the main commodities and sectors of Estonian economy. The calculations demonstrated that (direct) CO_2eq emissions associated with the oil shale-based electricity and thermal energy generation sector were "distributed" to the other sectors of the economy via intermediate consumption of the oil shale-based energy and it determined(s) high total (direct and indirect) CO_2eq emission intensities of the sectors separately and the economy as a whole;
- The EEIO approach together with the EEBT method was used to compile the consumption-based GHG inventory of Estonia. The evaluated emissions in the inventory were compared with the results of Estonia's production-based GHG inventory, which was completed based on the main rules established under the UNFCCC and the IPCC Guidelines. The results demonstrated that CO_2eq emissions associated with consumption in Estonia in 2005 were 18% higher than those associated with production;
- Carbon emissions associated with production and consumption of livestock-related products in Austria were examined using the FCA approach. Carbon emissions due to the changes in land use caused by production of soybeans imported as feed to Austria's husbandry sector were examined. The results of the study demonstrated that taking into account carbon emissions due to deforestation in Argentina and Brazil resulted in exceeding Austria's carbon emissions associated with the domestic production of livestock-related products for more than six times.

In detail, the results of the studies performed can be presented as follows:

LCA approach and oil shale-related industry

- LCA approach is considered to be an advanced and comprehensive tool for compiling and evaluating the input and output flows of materials and examining the environmental impact of a product system throughout its life cycle;
- Two limitations of the approach (i.e. spatial and temporal) were solved in order to examine the overall environmental pressure associated with oil shale resources and oil shale-based products produced and consumed in Estonia;
- The analysis of the environmental impact per GJ(15) of produced oil shale resource demonstrates that about 28 GJ of oil shale can be produced from 1 m^2 of the deposit, the production of 1 GJ of oil shale resource causes the generation of 35.5×10^{-3} t of waste rock, pumping of mine water in the amount of an average of 1.6 m^3 and emissions of about 874.4×10^{-6}t and 3.22×10^{-6}t of pollution into bodies of surface and groundwater. The generation of electricity and thermal energy is associated with CO_2 emissions into the atmosphere and thermal waste into bodies of water at values of about 300×10^{-3}t and 1.5 GJ per GJ of energy generated, accordingly. The generation of electricity causes the generation of hazardous waste at about 160×10^{-3}t of ash per GJ of electricity. The production of shale oil causes pollution emissions of VOCs and SO_2 in the amount of 100×10^{-6}t and 170×10^{-6}t per GJ of shale oil product, respectively, in Kiviter technology and 200×10^{-6}t and 20×10^{-6}t per GJ of shale oil product, respectively, in Galoter technology. The amount of hazardous waste generated per GJ of shale oil, in both technologies, is about 100×10^{-3}t. On the whole, the results are representative and can be used for comparison with the environmental pressure that is associated with the mining of other solid fuels (e.g. coal), with the production of other heavy fuels (e.g. oil), and with the generation of electricity and heat from other fuels (e.g. coal, gas, oil shale);
- The results of the study with the extended LCA approach showed that oil shale mining has a major pressure on land and water resources in the region. The mining of 28 GJ from 1 m^2, along with long-term mining of resources, significantly influences the quality of the land resource of the region. On the whole, the total mined-out area comprises about 13% (424 km^2) of the total territory of the extracting region of Estonia, about 27% of the mined-out territory is subsided and more than 45% is characterised as unstable;

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[15] The main pollution and waste amounts generated were presented.

- The continuous pumping of mine water from hydrologically sensitive environments has caused pollution of regional drinking water supplies and has led to overexploitation of deeper aquifers over the last 60 years;
- Pollution with sulphates emitted into bodies of surface water leads to the pollution of the surface as well as bodies of groundwater with sulphate and other contaminants. To date, the concentration of sulphates in most rivers and lakes of the region (e.g. the Kurtna lakes) is significantly higher than in the pre-mining period. The polluted water forms a 220 km^2 (170×10^6 m^3) "underground sea" in the exhausted mines;
- A high value of CO_2 emission per GJ of oil shale-based electricity and thermal energy generated makes Estonia a leader in CO_2 emissions per capita and TPES among European countries;
- The amount of solid waste generated in the process of electricity and thermal energy production is about 50% of the resource consumed in the PPs, and the resource is transformed into hazardous solid waste disposed of close to the PPs. The total area occupied for waste storage is about 20 km^2, contaminated with leachate generated polluting underground water of a territory of 9 km^2;
- The production of shale oil causes emissions of dangerous pollutants (e.g. H_2S, phenols and VOCs) into the atmosphere, but the values of emissions generated per GJ of shale oil product are not so high in the absolute value. However, the emissions contaminate the ambient air in the towns closest to the oil factories to a degree much higher than permissible levels. This poses a significant health threat to the inhabitants of these towns;
- About 96% of the hazardous waste generated in the process of shale oil production is stored in landfills. To date, about 96×10^6 t of hazardous waste is stored on a total area of 2.5 km^2. A large amount of leachate is formed in the process of precipitation infiltration. The pH of leachate varies from 8.47 to 12.54. On the whole, the area of polluted groundwater is 2.5 km^2, and the pollution reaches a depth of 40–52 m;
- The overall environmental pressure of the oil shale industry, estimated in the framework of the enhanced LCA, has clearly a long-term regional character; the facts should be taken into account in the process of the development of future agendas for each facility as well as the industry, in general.

The EEIO approach and Estonia's national GHG emissions inventories

- The standard IO approach is an advanced and comprehensive tool to provide a detailed picture, in monetary terms, of: (a) the total output of commodities by each sector of the economy; (b) the use of domestically produced and imported commodities of one sector for intermediate consumption to produce commodities in another sector of the economy; and (c) the final consumption of commodities (i.e. domestically produced and imported) within the economy and exported abroad;

- The extension of the monetary IO tables with data on environmental pressure (the EEIO analysis) allows assessment of the overall role of each sector in the pollution and the total environmental pressure of the economy of a country. Moreover, the EEIO is a suitable approach for analysing the environmental pressure embodied in commodities, which are widely traded in the globalised world and for illustrating the overall pressure associated with the consumption standards – "responsibility for environmental pressure" of each country of the world;
- The EEIO analysis for Estonia was completed for the first time on such a detailed level in the framework of the present study. It allowed to analyse how the different sectors of the Estonian economy are interrelated with each other, and the total GHG emissions associated with the economic sectors and commodities produced to be estimated. The focus was put on calculating of GHG emissions embodied in commodities traded bilaterally with Estonia. Energy-related and non-energy-related emissions were estimated. The study covered about 90% of the total GHG emissions in Estonia;
- Total CO_2eq emissions (i.e. energy-related and non-energy-related) associated with the production of commodities in Estonia were $17{,}278\times10^3$t in 2005. The majority of these emissions occurred in the energy sector. Non-energy-related CO_2eq emissions associated with agricultural products made up 5% of the total, and 4% of the non-energy-related emissions occurred in manufacturing;
- Estonia is an absolute leader among countries of the EU27 in the values of energy-related CO_2eq emissions per 1000 Euros of commodities produced by almost all sectors of the economy. The oil shale-based electricity and heat energy generation sector plays a key role in determining the GHG emissions intensity of Estonia's sectors. On the whole, the results of the production-based inventory demonstrated that about 75% of the total CO_2eq emissions were emitted directly from the energy sector of Estonia, which contributed 3% of the total output of the country in monetary terms. The implementation of the EEIO resulted in elaboration of the scheme of "distribution" of direct CO_2eq emissions from the electricity and thermal generation sector to the values of CO_2eq associated with other economic sectors;
- The data in the Estonia's consumption-based inventory demonstrated that the total CO_2eq emissions (i.e. energy-related and non-energy-related) associated with the consumption of commodities were $20{,}420\times10^3$t. The latter value exceeded the emissions associated with production by 18%;
- The percentage structure by sector of the CO_2eq emissions associated with consumption was nearly the same as for production-based emissions;

- Total CO_2eq emissions embodied in the export of commodities from Estonia were $4,132\times10^3$ tCO_2eq in 2005, and it made up about 24% of the total CO_2eq emissions associated with the production of commodities in Estonia;
- Total CO_2eq emissions embodied in the import of commodities during the same period were equal to $7,274\times10^3$ tCO_2eq or about 30% of the total CO_2eq emissions associated with the consumption of commodities in Estonia;
- Estonia "net imported" CO_2eq emissions embodied in commodities traded primarily from Russia, China, Kazakhstan, Ukraine and Belarus and 'net exported' to the EU27 countries, the United States, Norway and Switzerland in 2005;
- Among the EU27 countries, the main "net importers" of Estonia's CO_2eq emissions were the neighbouring countries of Latvia, Finland, Sweden and Lithuania. The main "net exporters" of CO_2eq emissions were Poland and Germany.

The FCA approach and Austria's husbandry sector

- The FCA was developed based on the main principles of LCA approach. The FCA is considered to be an advanced tool for tracing GHG emissions associated with a production of products or manufacturing process. The approach accounts for energy-related and non-energy-related direct and indirect GHG emissions, with the exception being GHG emissions from indirect changes in land use;
- The study performed in the present dissertation was focused on Austria's husbandry sector, rather than on Estonia's, because the Austrian sector is larger than the Estonian one in terms of livestock population and livestock-related product manufacturing (see footnote 1) and Austria's soybean imports are larger than that of Estonia: 499,931 t was imported by Austria in 2000, versus 22,085 t by Estonia;
- GHG emissions due to enteric fermentation, from manure management systems and from manufacturing and transportation of livestock-related products (recalculated to carbon) in Austria and Austria's trade partners were accounted for;
- The extension of the FCA approach allowed indirect GHG emissions due to changes in land use to be assessed, which occur far away from the consumption place of the product – e.g. emissions due to deforestation in Brazil and Argentina, which are embodied in soybeans imported to Austria from Germany, Italy and the Netherlands. Hence, the temporal and spatial dimensions of the data used were taken into account in the analysis under the FCA;

- Carbon emissions from domestic livestock production totalled 922 ktC/yr, and consisted of: (1) 723 ktC/yr (78%) from production; (2) 122 ktC/yr (13%) from enteric fermentation; and (3) 76 ktC/yr (8%) from manure management. About 83% of the total carbon emissions resulted from husbandry, i.e. from raising cattle and manufacturing dairy products. Carbon emissions from producing pig biomass (live animals and products) amounted to 17%;
- Carbon embodied in imports related to Austria's livestock sector amounted to 205 ktC; it equates to about 22% of Austria's total carbon emissions from domestic livestock production;
- Carbon embodied in livestock biomass exported from Austria was about 358ktC, and made up about 39% of Austria's total carbon emissions from domestic livestock production;
- In 2000, Austria's total carbon emissions under the domestic consumption approach comprised only 83% of the emissions accounted for under the domestic production approach, because of carbon emissions associated with exports from Austria were higher than carbon emissions embodied in imports to Austria;
- Carbon emissions imported to Austria indirectly due to deforestation in Brazil and Argentina because of production of soybeans were estimated based on two simple assumptions was applied: (a) soybeans indirectly (or directly) imported from Brazil and Argentina produced on land that was deforested by equal pieces over a 20-year period in Brazil and a 10-year period in Argentina; and (b) deforestation was taking place within one year;
- Carbon emissions due to deforestation estimated based on the assumption (a) were 0.3 MtC/yr or about 36% of Austria's domestic emissions in 2000. This resulted in positive net carbon emissions of 1.04 MtC from Austria's trade with livestock-related products versus 0.76 MtC from Austria's domestic consumption of livestock biomass;
- If the total area required for the production of soybean consumed by Austria's livestock had been deforested within one year (i.e. the assumption (b)), the resulting carbon emissions would be around 5.5 MtC in 2000 or more than six times greater than Austria's carbon emissions accounted for under the domestic livestock production approach.

4.2. Implications for the future

The studies presented in the dissertation demonstrated in detail the environmental pressure of the oil shale industry, assess the total (direct and indirect) CO_2eq emissions associated with Estonia's economy and analyse carbon emissions embodied in commodities bilaterally traded with Estonia and with Austria. The research carried out allowed a number of problems for future research to be identified.

In the context of the oil shale industry, an area for further research is to estimate ‘the integrated environmental pressure’ associated with the electricity and heat generation branch (i.e. with embodied pollution emissions, quantities of solid waste generated and disposed of, areas of land occupied, etc., resulting from the oil shale extracted for the consumption in this branch), and that of the shale oil production branch. The development of the methods for the evaluation of the cumulative pressure on the environment related to the unit of products (electricity, heat, shale oil) and taking into account international trade should be considered very challenging, especially in the era of globalisation and trade liberalisation. Since Estonia exported (exports) more than 10% of electricity produced and more than 50% of shale oil produced (data of 2002) this analysis would allow to estimate also “the overall responsibility” of consumers of oil shale products outside Estonia. This type of estimation is certainly important for the elaboration of the environmental policy of Estonia regarding the oil shale industry.

Compiling the production-based and consumption-based GHG inventories in the future it would be important to take into account emissions omitted from the present study, e.g. to include fugitive emissions due to refining petroleum products and solid fuel transformation, non-energy-related GHG emissions associated with more than 30 products (omitted from the present study) considered under the industrial processes sector and the agricultural sector (e.g. crops: legumes, fodder roots or dairy products such as butter and cheese). In addition, the examination of non-energy-related GHG emissions due to land use change and waste sectors should be included. It will allow more complete and accurate consumption-based GHG inventories to be compiled. Moreover, the examination of all sources of energy-related and non-energy-related GHG emissions should be completed using both the EEBT and MRIO approaches. This would allow a transparent analysis of GHG emissions associated with the bilateral trade to be carried out taking into account also GHG emissions embodied in (re)exported commodities.

The FCA approach can be implemented for a wide range of products produced in Estonia. To date, this approach has not been used in Estonia.

The integration of the results obtained in the framework of the enhanced LCA and FCA approaches with the modelling algorithm of the EEIO approach will allow a comprehensive analysis of the distribution of the overall environmental pressure and/or GHG emissions among the interacting sectors of the Estonian economy. Needless to say that this type of modelling effort will be highly resource demanding. However, the results of the comprehensive and detailed analysis obtained in the process of such modelling will form a solid basis for the decision-making process in the further development of the sectors of the national economy taking into account processes of globalization and objective context of SD.

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ACKNOWLEDGEMENTS

The research presented in this thesis has been carried out at the Chair of Biotechnology of the Department of Chemistry at the Tallinn University of Technology.

Here I would like to thank all the people who assisted and encouraged me in various ways during these PhD studies.

I would like to extend my special gratitude to my supervisor, Professor Raivo Vilu, who introduced to me the topics of the approaches of SD. His advanced ideas, useful and constructive suggestions and comments were very valuable in the process of my research towards completing my PhD thesis. Our discussions were intensive and effective.

Moreover, I would like to thank Matthias Jonas, PhD, from the International Institute for Applied System Analysis (IIASA), and Prof. Karlheinz Erb and Prof. Helmut Haberl from the Institute of Social Ecology (IFF) for having confidence in my work in their research groups.

Самые теплые слова благодарности моей семье за их поддержку и веру в меня. Я искренне признательна моей маме за ее жизненный оптимизм и мотивацию.Спасибо моему мужу за его поддержку.

This work was financially supported by the Estonian Science Foundation and the Estonian Ministry of Research and Education. The Kristjan Jaak Scholarship programme at the Archimedes Foundation is also acknowledged.

ABSTRACT

The SD concept has become a solid basis, inherent part and important objective for policy-makers at enterprise, industry, regional, national and/or global levels. A large number of indicator sets and accounting approaches have been developed to measure and characterize status and interactions between the SD dimensions (pillars).

The aim of the present dissertation was apply three approaches of SD: LCA, FCA and EEIO in the analysis and evaluation of environmental problems of Estonia and Austria. The advantages of the approaches, their limitations and opportunities for implications were analysed in the context of three case studies.

The extended LCA approach with solved temporal and spatial limitations was employed to analyse the interactions between oil shale-based products produced (oil shale, electricity, thermal energy, shale oil) and the environment of the north-eastern region of Estonia. The extension of the traditional LCA approach allowed, in addition to the environmental pressure per GJ of oil shale-based product produced, also to estimate annual contributions of the industry to the total environmental pressure of the country and in the region, and cumulative pressure on the environment accumulated since the commencement of oil shale mining and use. The results of the study demonstrated that the oil shale production and consumption lead (has led) to overexploitation of underground water resources and pollution of bodies of surface water, transformation and significant deterioration of land resources by mining activities, and huge amounts of hazardous waste disposal in the region.

The impact of the oil shale-based energy industry on the economy of Estonia was examined also in the framework of the EEIO approach. Production-based and consumption-based inventories of GHG were compiled and compared for the first time for Estonia. The analysis of the production-based inventory showed how the energy-based GHG emissions from the sector are “distributed” among the sectors of the Estonian economy and how the emission intensities of the different sectors influence the emission intensities of the other sectors. It was shown that the values of direct energy-related GHG emissions per monetary output (direct emission intensity) from the oil shale-based energy industry of Estonia were one of the highest among the countries of EU27. However, the direct emission intensities of other economic sectors were in line and comparable with the intensities of the other sectors of EU27. Nevertheless, “distribution” of GHG emissions of oil shale-based energy sector among the other sectors of the Estonian economy via intermediate consumption of commodities resulted in the total (direct and indirect) emission intensities of all sectors of the Estonian economy being increased and becoming higher than the total energy-related emission intensities of the respective economic sectors of other EU27 countries. The results of the consumption-based GHG inventory

compiled based on the EEIO and EEBT approaches demonstrated that Estonia “imported” more CO_2eq emissions than it “exported”. This means that the total CO_2eq emissions associated with the consumption of Estonia were higher than those associated with the production of commodities. The contribution of non-energy-related emissions, which were associated with manufacturing processes and agricultural activities to the total CO_2eq emissions of Estonia, was about 10% in both types of inventories. However, as not all categories of GHG emissions were taken into account in the study, the results of the analysis could change if all categories of non-energy-related emissions (e.g., GHG emissions of the LULUCF sector) were taken into consideration in the future.

The results of the third case study exemplified how carbon emissions due to changes in land use for production of soybean can alter the balance between two types of inventories of Austria. The extended FCA approach in which indirect carbon emissions due to changes in land use were accounted for demonstrated that if only direct energy-related and non-energy-related GHG emissions related to the husbandry sector of Austria were taken into account, it would result in a net export of carbon embodied in livestock-related products from Austria. However, taking into account indirect carbon emissions due to changes in land use for production of soybeans produced in Argentina and Brazil and consumed by Austria’s livestock, Austria becomes a net importer of carbon embodied. Hence, carbon emissions related to consumption in Austria’s husbandry sector become higher than those related to production.

In summary, the further development and extension of the accounting approaches provide a solid basis for understanding the interactions between economic activities and the environment and facilitate more objective decision making in order to achieve the main goal of SD: to guarantee the availability of natural resources, clear and healthy air and water, biological diversity, etc. for future generations.

KOKKUVÕTE

Säästva arengu (SA) mõiste on muutunud käesolevaks ajaks majandustegevusega kohalikul, riiklikul või rahvusvahelisel tasemel seotud poliitikaloome lahutamatuks osaks. SA erinevate dimensioonide (sammaste) vaheliste suhtenüansside mõõtmiseks ja tuvastamiseks on välja arendatud ning kasutusele võetud suur hulk näitajaid ning majandusarvestuslikke meetodeid.

Käesolevas dissertatsioonis on kolme SA arvestusmeetodi – LCA (elukaare hindamine), FCA (süsinikuvoogude täieliku arvepidamise) ja EEOI (keskkonna ja majanduse suhteid arvestava sisend-väljund analüüsi) abil analüüsitud Eesti ja Austria keskkonnaprobleeme. Antud arvestusmeetodite rakendamise võimalusi, piiranguid ja eeliseid analüüsiti kolme juhtumiuuringu kontekstis.

Laiendatud LCA arvestusmeetodit, mille puhul lähenemise ajalised ja ruumilised piirangud on "ületatud" kasutati analüüsimaks põlevkivitööstuse keskkonnasurvet Kirde-Eestis. Arvestusmeetodi laiendatud versioon võimaldas uurida mitte ainult kõikide põlevkivitoodete tootmise keskkonnasurvet energiaühiku (GJ) kohta, vaid ka põlevkivi kaevandamise ning elektri, soojusenergia ja põlevkiviõli tootmise osa regionaalses keskkonnasurves aasta ning kogu põlevkivitööstuse eksisteerimise aja jooksul. Uuringu tulemused näitasid, et kõige suurema surve all Kirde-Eestis on piirkonna vee ja maa ressursid tingituna põhjaveeressursside ületarbimisest ja pinnaveekogude reostamisest, maa väärtuse vähenemisest tänu kaevandamisele ning suurte koguste ohtlike jäätmete ladustamisele.

Põlevkivienergeetika mõju Eesti majanduse efektiivsusele uuriti ka kasutades EIOA arvestusmeetodit. Koostati (esmakordselt) Eesti tarbimispõhine KHG inventuur ning võrreldi seda IPCC-le iga-aastaselt esitatavate tootmispõhiste inventuuridega. Tootmispõhise inventuuri raamides uuriti, kuidas energiasektoris toodetud kasvuhoonegaaside heitmed liiguvad (arvestuslikult) Eesti majanduses ning kuidas energiasektori kasvuhoonegaasiheitmete intensiivsus (GHG emissions intensity – e.k. KHGI) mõjutab Eesti majanduse teiste sektorite KHGI-sid. Nagu teada, on Eesti põlevkivi baasil toimiva energiasektori KHGI ELi riikide kõrgeimate seas. Meie uuringud näitasid, et otsesed (energia tarbimisest sõltumatud) KHGI-d teistes majandussektorites on võrreldavad ülejäänud ELi riikide vastavate sektorite näitajatega. Kui aga "jagada" põlevkivist tulenevad KHG heitmed ümber teiste Eesti majandussektorite vahel läbi majandustegevuse, siis ületas kõigi Eesti majandussektorite KHGI teiste ELi riikide vastavate majandussektorite kogu (otsese ja kaudse) KHGI. Tarbimispõhise KHG inventuuri koostamine kasutades EIOA ja EEBT arvestusmeetodeid näitas, et Eesti CO_{2eq} "import" rahvusvahelise kaubanduse kaudu on suurem, kui "eksport" kaubavahetuse kaudu välismaale. See tähendab, et Eesti tarbimisega seotud CO_{2eq} heitmed olid suuremad, kui kaupade tootmisega seotud heitmed. Tootmisprotsesside ja põllumajandustegevusega seotud energia tarbimisega mitteseotud KHG heitmete panus kogu Eesti CO_{2eq} heitmetesse oli mõlemas inventuuritüübis umbes 10%. Edasiste võimalike arenduste mõttes tuleb märkida, et käesolevas uuringus ei arvestatud siiski kõiki KHG heitmekategooriaid ning seetõttu võib oodata, et juhul kui tulevikus võtta arvesse kõik energiaga mitteseotud heitmed nagu maakasutuse, maakasutuse muutuste ja metsandussektori, samuti jäätmesektori KHG heitmed, võivad tulemused (mõnevõrra) muutuda.

Kolmanda juhtumiuuringu tulemused näitasid, kuidas maakasutuse muutustest tulenevad KHG heitmed võivad muuta kahest kirjeldatud inventuurist tehtud järelduste iseloomu. Laiendatud FCA arvestusmeetod, kus võeti arvesse maakasutuse muutustest tulenevate kaudsete süsinikuheitmete osa näitas, et arvestades vaid otseste energiaga seotud ja energiaga mitteseotud KHG heitmetega Austria loomakasvatuse sektoris, oli Austria tänu loomakasvatusega seotud toodete ekspordile süsiniku eksportija. Võttes aga arvesse maakasutuse muutusest tulenevaid kaudseid süsinikuheitmeid, mis on seotud sojaubade tootmisega Argentiinas ja Brasiilias, mida aga tarbivad Austria kariloomad, muutus Austria süsiniku netoimportijaks.

Kokkuvõttes, SA arvepidamise edasiarendamine ja laiendamine võimaldab tõsta andmete kvaliteeti ning loob tugeva aluse majandustegevuse ja keskkonna vaheliste suhete mõistmiseks ning otsuste tegemiseks, et saavutada SA põhilist eesmärki: garanteerida tulevastele põlvkondadele loodusvarade kättesaadavus, puhas ja tervislik õhk ja vesi, bioloogiline mitmekesisus jpm.

ORIGINAL PUBLICATIONS

PUBLICATION I

O. Gavrilova, M. Jonas, K-H. Erb, H. Haberl. International trade and Austria's livestock system: Direct and hidden carbon emission flows associated with production and consumption of products. *Ecological Economics* 2010, 69, 920–929.

Ecological Economics 69 (2010) 920–929

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

International trade and Austria's livestock system: Direct and hidden carbon emission flows associated with production and consumption of products

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ARTICLE INFO

Article history:
Received 1 August 2008
Received in revised form 11 November 2009
Accepted 12 November 2009
Available online 3 December 2009

Keywords:
Hidden carbon emissions
Sharing responsibility
Kyoto Protocol
Deforestation
Full carbon accounting
Life cycle analysis

ABSTRACT

The Kyoto Protocol created a framework of responsibilities and mechanisms to mitigate climate change by reducing the emissions of greenhouse gases (GHGs) into the atmosphere. The Protocol stipulates accounting and reporting of GHG emissions and removals, such as energy use, industrial processes, agriculture, waste and net emissions resulting from land use, land-use change and forestry (LULUCF) activities. Emissions reported according to the rules set by the Kyoto Protocol do not include GHG emissions outside a country's boundaries resulting from the production of imported goods or services. As a result, GHG accounts constructed according to the Kyoto Protocol reflect the GHG emissions resulting from the production system of a country, but not all the emissions resulting from the consumption of goods and services within the country. However, as previous studies demonstrate, a country's emission balance changes remarkably if emissions related to goods or services imported and exported are taken into account. Here, we go beyond the aforementioned studies which mainly focus on GHG emissions from fossil fuel combustion. We assess, in a first-order approach, upstream emissions that result from LULUC activities outside a country while the produced goods are consumed within the country. In our study we focus on Austria's livestock system to elucidate the difference between production and consumption-related emissions accounting approaches. We study direct and 'hidden' (embodied) GHG emissions associated with Austria's bilateral trade in livestock and livestock-related products, based on the integration of full carbon accounting (FCA) and life cycle analysis (LCA).

1. Introduction

The Kyoto Protocol (KP) is considered to be one of the most important documents of global climate policy. A number of mostly economically developed countries, the so-called Annex B countries, have agreed to reduce their GHG emissions by about 5% below the 1990 level until the end of the first commitment period, i.e., 2008–2012 (UN press release, 1998). Emissions from five sectors (energy, solvent and other product use, industrial processes, agriculture and the waste sector; defined as initial assigned amount) are accounted in order to determinate compliance with the commitment. In addition, some emissions and removals resulting from afforestation, reforestation and deforestation activities (ARD) are mandatorily included. Progress towards meeting the emission targets of the Parties to the KP is monitored in accordance with approved methodologies developed in cooperation with the Intergovernmental Panel on Climate Change (IPCC) (1997, 2000, 2006).

However, in the current era of rapid globalization, GHG emissions reduction policies as agreed under the KP might be foiled by a surging trade of emission-intensive products from non-Annex B countries to Annex B countries. This problem is meanwhile increasingly discussed in the scientific literature (Gosbey, 1999; Ahmad and Wyckoff, 2003; Charnovitz, 2003; Frankel, 2004; Ward, 2004). The GHG inventories that follow the IPCC Guidelines (IPCC, 1997, 2000, 2006) take a production-based approach: GHG emissions are assigned to the country where a good is produced, not to the country where the goods are consumed. A situation in which some countries adopt binding targets to reduce their GHG emissions and others do not, creates incentives to produce emission-intensive goods (above all, raw materials or semi-manufactured goods) in countries without binding emission reduction targets and import these goods to countries that are subject to GHG emission limitations. Due to trade liberalization, many companies of advanced economies produce goods outside their home countries, often in developing countries with cheap labor, low resources or capital costs, lenient pollution control, etc., for import into their economies; the same result is observed if companies operate supply chains that stretch far beyond their domestic markets (EC, 2006). Thus, considerable GHG emissions might emerge due to the supply of goods or services to final

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0921-8009/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolecon.2009.11.015

consumers in developed economies that are currently accounted for as emissions of developing countries not subject to emission controls. Consequently, under current arrangements, national emission accounts could be embellished owing to international trade to shift emissions from countries with GHG emission reduction targets to countries lacking such targets. In extreme cases, this could mean that a country could even achieve its commitments under the KP despite an increase in the GHG emissions resulting from the production of the goods and services consumed within that country.

Numerous studies have considered the role of international trade and the consequences for national carbon emission accounts, that is, on the difference between domestic production and domestic consumption. Ahmad and Wyckoff (2003) observed that between 1995 and 2000 exports of goods from OECD countries to the rest of the world increased by 7%, but imports from the rest of the world to the OECD countries grew by 47%. Ward (2004) noted that in 1995 CO_2 emissions embodied in the imports of OECD countries exceeded those embodied in exports by around 0.5 Gt CO_2 or about 2.5% of global CO_2 emissions. Schaeffer and De Sa (1996) showed that CO_2 emission embodied in net Brazilian exports (imports minus exports) amounted to 11.4% of Brazil's total CO_2 emission in 1990. Munksgaard and Pedersen (2001) found that CO_2 emissions embodied in imported/exported goods diminished Denmark's total CO_2 emissions by 7 million tonnes in 1994. Similar studies carried out for a wide range of countries (Kondo et al., 1998; Lenzen, 1998; Tolmasquim and Machado, 2003; Peters and Hertwich, 2006, 2008; Mäenpää and Siikavirta, 2007) showed that accounting for CO_2 emissions from fuel combustion in the process of manufacturing taking into account international trade can significantly alter national GHG balances.

There are, however, still several methodological challenges related to the accounting GHG emissions associated with domestic consumption. Whereas previous studies estimated GHG emissions from fossil fuel combustion and consumption of goods, often disaggregated by branches, they did not account for the entirety of national carbon flows. As some industrial sectors are driving forces for land-use change related GHG emissions, in a full carbon accounting (FCA) approach it is essential to take all flows into account.

In this article we elaborate on the difference in GHG emissions between two accounting principles, domestic production and domestic consumption, adopting a full carbon perspective. The main idea behind FCA is to estimate all national carbon flows, i.e., flows related to the terrestrial biosphere system (gross primary production, net primary production, flows due to disturbances and changes in land use, etc.) and human society (fuel combustion, industrial processes, etc.) (Steffen et al., 1998; Jonas et al., 1999; Orthofer et al., 2000; Jonas and Nilsson, 2001; Erb et al., 2008). We aim at quantifying, in a first-order approach, consumption-related upstream emissions that result from (a) fossil fuel consumption in the production process, and (b) land-use activities outside a country's national borders, taking Austria as an example. Because we aim at exploring the differences in the accounting schemes at a more general level, and due to the unavailability of data for full carbon accounting, we restrict our study to Austria's livestock production system, including Austria's bilateral trade with livestock products. We chose the livestock production system because it combines the two aforementioned upstream emissions. Moreover, Erb et al. (2009) have demonstrated that there is a large and growing 'disconnect' between producing and consuming areas for biomass-based products and that a better understanding of conversion processes such as those involved in livestock rearing is needed to better understand the implications of the effects of trade on this system.

Thus, we do not provide a Full Carbon Account for the whole of Austria but comply with it from a consistency point of view in that we restrict our analysis to a complete segment in this account, Austria's livestock production-consumption system. Hence, our Input–Output (IO) based approach aims at integrating emissions from industrial processes and emissions associated with land-use change, which was not done in previous papers (Schaeffer and De Sa, 1996; Kondo et al., 1998; Lenzen, 1998; Ahmad and Wyckoff, 2003; Tolmasquim and Machado, 2003; Peters and Hertwich, 2006; Mäenpää and Siikavirta, 2007). Our accounting framework can serve as a starting point for further investigations related to estimating GHG emissions embodied in international trade and be used to complement, or even be included in, the KP at a later stage or to contribute to reducing emissions from deforestation on the global level.

2. Methodology and Data

In order to compare GHG accounts referring to domestic production and domestic consumption of Austria's livestock system we use a combination of life cycle analysis (LCA) and FCA (Jonas et al., 1999; Orthofer et al., 2000; Jonas and Nilsson, 2001). This combination allows evaluating the main input–output flows of a system. The basic difference of the two approaches is expressed in Eq. (1) (Ahmad and Wyckoff, 2003). Whereas production-based schemes account for carbon flows resulting from national production processes of goods (E_{DP}), consumption-based approaches refer to the consumption of goods (E_{DC}), and thus associate carbon flows with the final consumption of goods.

$$E_{DC} = E_{DP} + E_{IM} - E_{EX} \tag{1}$$

E_{DC} — carbon emissions resulting from domestic consumption; E_{DP} — carbon emissions resulting from domestic production; E_{IM} — carbon emissions embedded in imported products; and E_{EX} — carbon emissions embedded in exported products.

Fig. 1 visualizes our accounting. The CO_2 and CH_4 emissions related to Austria's livestock biomass production (cattle and pigs) are: emissions resulting from enteric fermentation (C_CH_4) and manure management (C_CH_4); emissions from production processes (C_CO_2); and emissions from transportation of animal products (C_CO_2) and product (cattle and pig meat, milk) manufacturing (C_CO_2). Carbon emissions from land-use change due to animal feed production (C_CO_2) are accounted as 'hidden' emissions. Carbon input via feed intake by animals and land requirements are estimated as well to evaluate biomass demand and the land needed for the production of livestock feedstuff. Flows associated with the import of products increase Austria's GHG emissions (carbon emissions embodied in products are considered), while carbon flows associated with exported goods are subtracted. GHG flows are calculated in units of thousand tonnes of carbon per year (kt C/year), and land area used for animal feed production is estimated in units of thousand hectares (kha).

Our study refers to the year 2000. Data on domestic production and Austria's bilateral trade with livestock products (living animals, meat, milk and milk products) were obtained from FAO databases (FAOSTAT, 2005, 2009). FAO's databases contain data by country of origin/final destination and traded product. They allow tracing the trade network structure of Austria.

In order to account for the upstream carbon flows (Fig. 1), an LCA approach is employed. It allows evaluating all input–output flows associated with a product during its full life cycle. Methane emission factors for animal enteric fermentation and manure management systems are taken from the IPCC Guidelines (IPCC, 1997, 2006). The calculation of carbon emissions due to milk and meat production are based on the slaughter weight of animals or milk yield per cow. Multipliers, which allow calculating carbon emissions from product processing and transportation are taken from the GEMIS database (www.gemis.de). They are used to calculate upstream emissions, within and outside Austria's territory. Emissions from transport are estimated on the basis of transport distances and emissions per tonne-km in dependence of the means of transport. Transport within Europe is assumed to occur by truck, and by ship if trade is taking

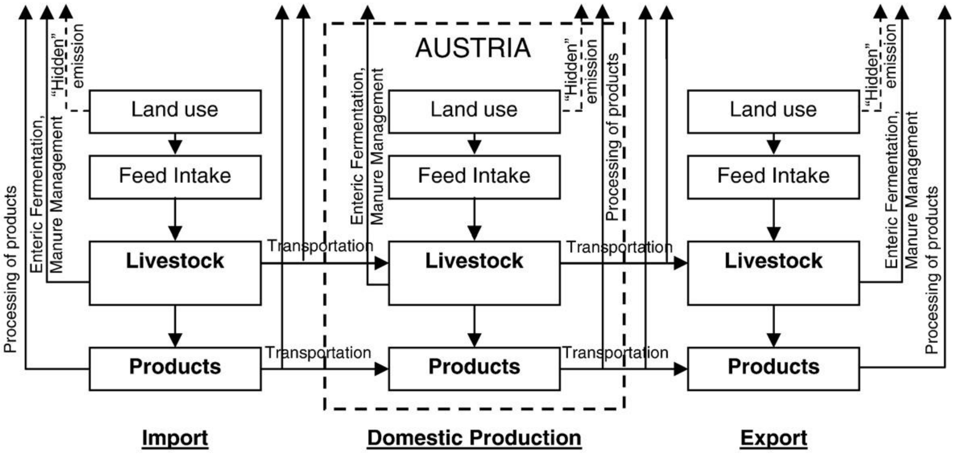

Fig. 1. System description of carbon flows related to Austria's domestic production and its bilateral trade of living animals and animal products.

place between Austria and a non-European country. International transport distances between any two countries are estimated by taking the distances between their capitals as a proxy. The carbon input via feed intake and the land required for animal feed production (e.g. grasslands, fodder crop areas) is estimated by considering the annual gross energy demand of a livestock population. Agricultural yields for primary (e.g., corn) and secondary (e.g., straw) feedstuff, and average harvest conditions by employing harvest indexes are used (Wirsenius, 2000; Krausmann et al., 2008). All assumptions and calculations are summarized in Appendix A.

Not only can traded livestock and livestock products be a source of GHG emissions, but also imported/exported feedstuff. Continuously growing demand in feedstuff causes degradation of soils, over-exploitation of grasslands and deforestation (Steinfeld et al., 1996) and result in emissions of carbon. For reasons of data availability, we restrict our assessment to the area required for Austria's imports of soybean and soybean products (e.g., soybean cake). Other feedstock imported to Austria (e.g., cereals and co-products) and feedstuff exported from Austria (e.g., rape-cake) is assumed to be carbon-neutral during cultivation and production. Soybean products are the largest fraction (64%) of feedstock imported to Austria in the year 2000 (equivalent to 11% of Austria's total imports) (FAOSTAT, 2005). Austria's domestic production of soybean is negligible (3.6% of total soybean consumption in 2000), indicating Austria's dependence on soybean product imports, which increased 39-fold between 1961 and 2004 (from 14.6 thousand tonnes (14.6×10^3) in 1961 to 387×10^3 t in 1980 to 577×10^3 t in 2003) (FAOSTAT, 2009). The linear trend in increase of soybean product consumption is typical for most countries of the world (Fig. 2).

The increase in demand led to the remarkable increase in cultivated areas from 24 million hectares (24×10^6 ha) in 1961 to 57×10^6 ha in 1990 to 83.6×10^6 ha in 2003 and to 94.9×10^6 ha in 2006 (FAOSTAT, 2009). There are four main producers of soybean in the world, their shares of the total world production being 46.5% — USA, 20.3% — Brazil, 12.5% — Argentina, and 9.5% — China in 2000 (FAOSTAT, 2009).

Cultivation of soybean causes considerable negative environmental impacts in producer countries, mainly N_2O emissions to the atmosphere resulting from the use of nitrogen fertilizers in the USA and China (Smil, 2000; Chen et al., 2000; FAS online, 2000; Ramankutty and Foley, 1999) and CO_2 emissions due to direct and indirect land-use changes for the expansion of cultivated areas in Brazil and Argentina (Fearnside, 2001, 2005; Shean, 2003, 2004; Grau et al., 2005; Nepstad et al., 2006).

In Brazil, soybean cultivation area has expanded from 0.24×10^6 ha in 1961 to 18.4×10^6 ha in 2003, mostly due to indirect and direct deforestation. The expansion in soybean cultivation area began in the 1980s and 90s, when the 'Center-West' regions of Brazil (the *Cerrado*) were cultivated for additional agricultural production, in particular soybeans. Until 1980s, soybean production in Brazil was small and took place on traditional agricultural areas in the south of Brazil (Flaskerud, 2003; Dros, 2004). The areas cultivated with soybeans had mostly previously been deforested for cattle ranching or cultivation of other agricultural crops. As a consequence, soybean production displaced ranches and small-farmers further into the Brazilian Amazon forest (Fearnside, 2001; Greenpeace, 2006; Margulis, 2004; Nepstad et al., 2006; McAlpine et al., 2009; Volpi, 2007), thus probably contributing indirectly to deforestation (Fig. 3A). This expansion affected forest areas also directly due to the building of transportation utilities (ports, highways, etc.) in order to reduce transportation costs.

In Argentina, soybean production area increased from 0.001×10^6 ha in 1961 to 14.3×10^6 ha in 2003. Between the 1970s and 1990, about 90%

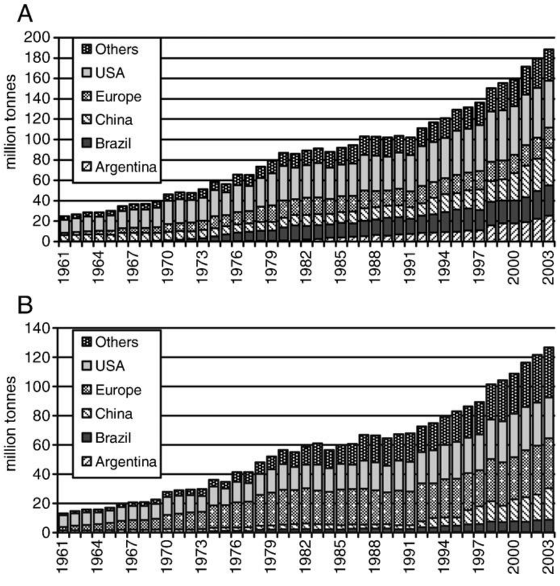

Fig. 2. The world's consumption of soybean (A) and soybean products (B) by main country- and region-consumer, in 10^6 t.
FAOSTAT, 2009.

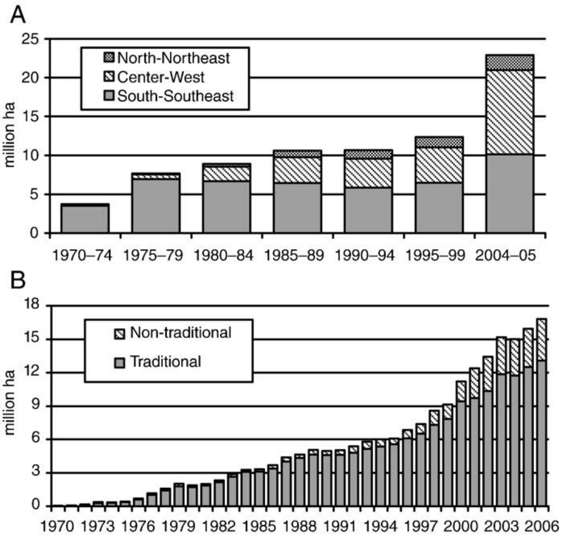

Fig. 3. Soybean production in (A) Brazil and (B) Argentina by region in 10^6 ha. (A) Brazil: *south-southeast* (*traditional agricultural areas*) — Rio Grande do Sul, Santa Catarina, Parana, Sao Paulo, Minas Gerais; *center-west* — Mato Grosso, Mato Grosso do Sul, Goias, Federal District; *north-northeast* — Rondonia, Tocantins, Maranhao, Piaui, Bahia, and others. (B) Argentina: *traditional agricultural areas* — Buenos Aires, Cordoba, San Luis, Santa Fe; and *non-traditional agricultural areas* — Chaco, Entre Rios, Formosa, Misiones, Salta, Santiago del Estero, and Tucuman.
Randall et al., 2001; Shean, 2003; and SAGPyA, 2009.

of planted areas were located in traditional agricultural provinces (Fig. 3B) (SAGPyA, 2009). The soybean expansion took place on existing farmland for other crops and pastures in these provinces (Randall et al., 2001). Since 1990s, the production began to expand into non-traditional agricultural areas (mostly forested areas), increasing from 0.43×10^6 ha in 1991 to 3.77×10^6 ha in 2007 (i.e., from 9% to 23% of the totally planted soybean area) or 0.19×10^6 ha/year on average (Fig. 3B) (SAGPyA, 2009). This expansion occurred in Chaco bush savannas and Yungas moist montane-subtropical forests (Dros, 2004). About 56% (e.g. 12.8×10^6 ha) and 22% (e.g. 3.4×10^6 ha) in 2005 of the total cultivated area for soybean production occurred on indirectly and directly deforested lands in Brazil and Argentina, respectively (Fig. 3).

The calculation of 'hidden' carbon flows emitted due to land-use change outside Austria's territory (in Brazil and Argentina) is based on estimates for: (1) the amount of soybean and soybean product imports, and (2) the expansion of agricultural areas for soybean production in producing countries. The FAO dataset contains detailed information by country on soybean production, consumption, trade (a detailed analysis for the data since 1986 and afterwards), and areas of cultivation (FAOSTAT, 2005). However, the trade dataset refers to countries which export products to Austria; these countries are not necessarily those where the products were produced (Table 1). For example, according to the FAO, Austria's soybean import mainly originates from Germany, Italy and The Netherlands (Fig. 4). But their production of soybeans is negligible in the global context and, with the exception of Italy, not even sufficient to cover the amount transported to Austria. These countries imported soybean products mainly from the USA, Brazil and Argentina. Their import volumes have changed continuously (Table 1).

To properly assess the land-use component of upstream carbon flows, an adjustment of trade data was necessary, as displayed in Fig. 5. [1] The adjustment of trade data is based on the assumption that exports of the countries of origin consist of domestically produced and imported soybeans, which is described by the domestic material input (DMI, the sum of domestically produced and imported products). [2] An example that demonstrates how we performed these adjustments, Brazil's soybeans exported to Austria through Germany, with a more detailed description of the steps taken, is provided in Appendix B. The same scheme is used in order to calculate Brazil's and Argentina's soybeans exported to Austria through The Netherlands and Italy.

To estimate in detail the 'hidden' carbon flows related to Austria's traded livestock products due to land-use change in South America, a large body of knowledge on accurate temporal and spatial data would be required. Such information, however, is currently not available. Therefore, we proceed by employing simplified assumptions to provide a connection between Austria's soybean consumption and the land-use expansion for soybean production and deforestation that took place in South America. Austria imports directly and indirectly soybeans from Brazil and Argentina (Table 1). The soybeans were produced on areas which historically were covered by forest and deforested due to Austria's need for soybean products for livestock feeding. This makes Austria a (here the only) 'responsible' beneficiary of this deforestation and the carbon emissions that occurred as a result of this activity.

In order to estimate Austria's deforestation 'responsibility' in Brazil and Argentina, a simplified approach based on simple assumptions is applied: (a) soybeans indirectly (or directly) imported from Brazil are

Table 1
Domestic production of soybeans in Germany, The Netherlands and Italy (in 1000 t) and the total import of soybeans by country [in %].
FAOSTAT, 2009.

Country	Year	Production 1000 t [harvested area, 1000 ha]	Import, 1000 t	Import from…[in %]				
				Brazil	Argentina	The Netherlands	The USA	Other
Germany	1986	n.d. [n.d.]	5385.5	17.6	20.4	11.1	49.9	0.9
	1990	4.7 [2.4]	4853.0	22.2	27.3	18.4	27.0	5.1
	1995	1.0 [0.5]	4741.0	22.5	17.8	17.0	40.5	2.2
	2000	1.0 [0.5]	5727.5	30.5	10.7	37.3	20.3	1.2
	2005	n.d. [0.9[a]]	6498.2	36.8	5.0	42.0	9.3	6.9
The Netherlands	1986	–	4151.7	16.2	18.3		62.7	2.8
	1990	–	5233.4	32.6	23.4		31.3	12.7
	1995	–	6738.2	22.6	20.8		48.8	7.8
	2000	–	6852.7	46.6	12.2		36.1	4.7
	2005	–	9832.8	59.1	23.0		10.4	7.5
Italy	1986	806.1 [232.4]	2639.3	21.0	18.4		59.4	1.2
	1990	1750.5 [521.2]	2123.3	51.8	24.7		21.0	2.5
	1995	732.4 [195.2]	3207.6	31.4	42.8		25.2	0.6
	2000	903.5 [252.6]	3001.4	21.5	65.5		11.1	1.8
	2005	388.5[b][152.3]	4002.2	37.5	51.2		3.0	8.4

[a] Interpolated.
[b] The data of 2003.

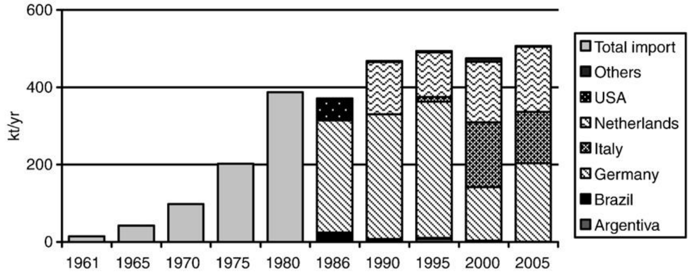

Fig. 4. Import of soybeans, including soybean cake, to Austria (in kt/year) by country-importer, 1961–2005. FAOSTAT, 2009.

produced on indirectly and directly deforested land; and (b) about 10% of the soybeans produced in Argentina and imported to Austria are from non-traditional agricultural areas that had been deforested.

'Hidden' carbon emissions embedded in soybean products fed to Austrian livestock are investigated under the simplifying assumption that equal pieces of land were deforested over a 20-year period in Brazil and a 10-year period in Argentina. We consider this assumption a good approximation of reality. As an extreme case, which we include in order to estimate the upper limit of the possible effect, we also quantify the extreme case of instantaneous deforestation (i.e., deforestation within 1 year).

3. Results

Carbon emissions associated with Austria's livestock and livestock-related products are estimated using two accounting principles: domestic production and domestic consumption. Table 2 presents Austria's production, import and export of livestock biomass in 2000. Austria mainly traded with countries of Western and Eastern Europe. Germany was leading the export to Austria of live cattle, cattle meat and cow milk (95.3%, 53.8% and 59.7% of the total import value, respectively). The main importer of Austria's products was Italy: 59.3% of the total export of live cattle, 39.1% of cattle meat and 45.6% of the total export of cow milk went to Italy.

Germany was also leading the export of pig products to Austria. Germany's exports of pig meat to Austria made up 72.1% of the total value of pig meat imported by Austria. Austria's imports of living pigs totaled 283,394 heads, 99.3% of which are from Germany. Austria exported pig meat mainly to Italy (31.4%), Germany (19.9%) and Romania (10.4%) and living pigs mainly to Croatia (44%), Germany (35.0%) and Italy (20.7%).

Carbon emissions from domestic livestock production, totaled 922 kt C/year, is consisting of: (1) 723 kt C/year (78%) from production, (2) 122 kt C/year (13%) from enteric fermentation and (3) 76 kt C/year (8%) from manure management. About 83% of the total carbon emissions resulted from husbandry, i.e., from raising cattle and manufacturing dairy products (milk). Carbon emission from producing pig biomass (live animals and products) amounted to 17%. Fig. 6 summarizes the main results on carbon emissions evaluated according to the two accounting principles for the year 2000.

Carbon 'embodied' in imports related to Austria's livestock sector amounted to 205 kt C (Fig. 6; Tables 3 and 5). Total emissions resulted from: 143 kt C (70%) from fuel combustion during production; 31 kt C (15%) from transportation (products to Austria); and 31 kt C (15%) from enteric fermentation and manure management. Carbon 'embodied' in livestock biomass exported from Austria was about 358 kt C, whereas more than 259 kt C (72%) was emitted from livestock product manufacturing; 38 kt C (11%) was emitted from livestock biomass transportation and 61 kt C (17%) from enteric fermentation and manure management.

The ratio of imported to exported carbon for Austria was 0.57 (Table 3). Thus, Austria was a net exporter of embodied carbon in 2000.

Considering trade, Austria's carbon emissions related to domestic consumption of livestock products was only 768 kt C. This means that Austria's emissions due to domestic consumption were about 153 kt C less than its carbon emissions associated with domestic production (Fig. 6, Table 5).

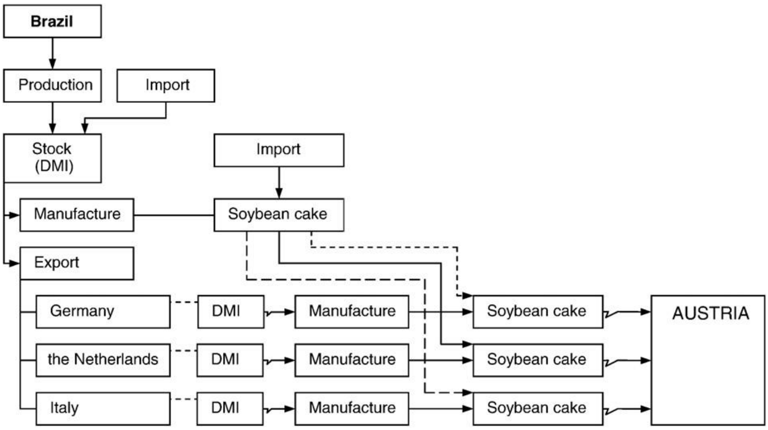

Fig. 5. Algorithm to handle soybean and soybean cake imported from Brazil as producing country through Germany, The Netherlands and Italy as third countries (the same algorithm is used for estimating the amounts of soybean and soybean cake imported from Argentina).

Table 2
Austria's domestic production, import and export of livestock biomass in 2000.

	Import	Domestic production	Export	Balance
Living animals, [heads/year]				
Cattle	34,367	2,171,681	144,593	2,061,455
Pigs	283,394	3,430,995	26,188	3,688,201
Cattle meat, [t/year]	14,790	203,489	70,034	148,245
Pig meat, [t/year]	108,467	620,404	134,456	594,415
Milk, [t/year]	762,525	3,364,290	1,332,194	2,794,621

Table 4
Total amount of soybeans harvested for consumption in Austria and land area required for soybean cultivation.

Country of origin of soybean cultivation	Soybean ‘indirect’ import to Austria, kt/year	Land required for cultivation, kha	Area deforested directly (d) and indirectly (i) for soybean production, %
Argentina	172.800	73.846	d: 10%
Brazil	207.709	86.546	i: 40%
United States of America	109.227	42.667	
Total	489.736	203.059	

On average, 0.5 ha was used in order to produce 1 t of carbon consumed by Austrian livestock: the total land required for Austria's livestock was about 2460 kha, and the total feed intake about 5709 kt C. An equivalent of 800 kha was exported for livestock and livestock-related products consumed outside of Austria. On average, 0.7 ha was required for producing 1 t of carbon contained in feedstock (market and non-market feed and grazing) consumed by animals (live animals and products) exported to Austria. The total land required was about 604 kha and the feed intake about 76 kt C.

About 490 kt soybean products (fresh matter) imported to Austria in 2000 required an area of 203 kha; more than 381 kt (75% of Austria's total soybeans import) were cultivated in Brazil and Argentina on an area of 160.4 kha, where about 42 kha of land had directly and indirectly been deforested (Table 4).

The average stock of biomass of growing trees of Argentina's forest ranges from either 105 to 245 t DM (tonnes of dry matter, DM) per hectare, or from 50 to 122 t C/ha with the carbon content (CC) being 0.5 t C/t DM (Gasparri et al., 2008). In Brazil, the average growing stock of the *Cerrado* (the Mato Grosso) region is about 253.8 t DM/ha (127 t C/ha; Nogueira et al., 2008).

Carbon emissions resulting from deforestation in Argentina and Brazil due to the cultivation of soybeans consumed in Austria are 277.4 kt C in 2000. The case assumes constant land clearing over a period of 20 years in Brazil and 10 years in Argentina: in total 1.7 kha/year during 1980–1990 and 2.4 kha/year during 1991–2000, respectively (Table 5). Austria's balance of carbon emissions estimated in accordance with the domestic consumption accounting principle would increase to about 841 kt C, surpassing Austria's emissions calculated according to the domestic production principle by about 1.13 kt C/kt C (Table 5).

4. Discussions and Conclusion

It is well known that international trade plays a large and rapidly increasing role in matching supply and demand for biomass-based products (Krausmann et al., 2008; Erb et al., 2009; Krausmann et al., 2009). In order to contribute to a better understanding of this process in terms of its implications on national-level greenhouse gas emission balances, we here compare two accounting principles, domestic production and domestic consumption, to estimate carbon emissions related to the Austrian livestock system. The study aims to contribute to the ongoing discussion on and the search for effective instruments to reduce CO_2 emissions to, and concentration in, the atmosphere in the era of global trade liberalization. We are particularly interested in evaluating how Austria's emissions balance changes if the carbon accounting is based on a consumption approach instead of the conventional production-based approach, therefore focusing our attention on the lifestyle of consumers.

We integrate the FCA and LCA approaches in order to estimate emissions according to domestic production and domestic consumption for a complete segment of Austria's socioeconomic system, its livestock system. Our study shows that methods are readily available to estimate direct carbon emissions (CO_2 and CH_4) from domestic livestock and the combustion of fossil fuels in the processes of product

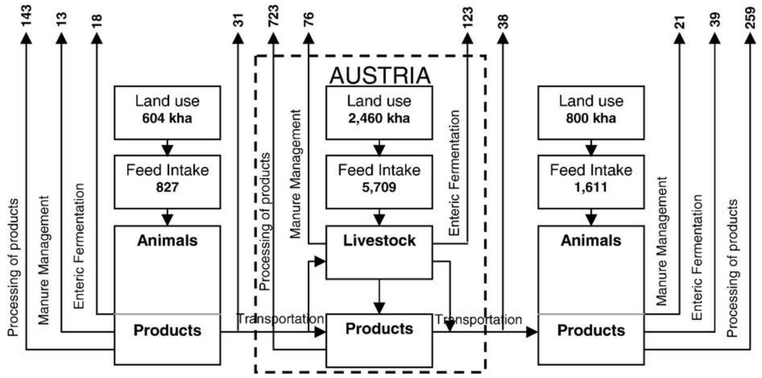

Fig. 6. Total carbon emissions (in kt C) from domestic production, import and export of livestock biomass (cattle, pigs) in 2000.

Table 3
Carbon emissions (in kt C) embodied in Austria's import and export in 2000, broken down into world regions.

	North Africa and West Asia	South and Central Asia	East Europe	West Europe	Sub-Saharan Africa	Latin America and Caribbean	North America and Oceania	East Asia	Total
Import			16.231	175.356	0.101	2.210	10.823	0.035	204.756
Export	6.557	1.169	29.273	315.225	0.210	0.633	2.984	2.087	358.137

Table 5
Carbon (in kt C) embodied in animal products traded with Austria and in soybean cake imported to Austria in 2000.

	Carbon 'embodied' in IMPORT	Emission related to domestic production (E_{DP} in the formula (1))	Carbon 'embodied' in EXPORT	Emission related to domestic consumption (E_{DC} in the formula (1))
Carbon embodied in livestock biomass	204.756	921.761	358.137	768.380
Carbon embodied in livestock feed imported to Austria [area deforested, ha/year]	277.4 [2402]			1045.8

manufacturing and transportation. Our study highlights the need and importance of expanding the production-related emissions approach and including upstream ('hidden') carbon emissions resulting from land use — in our case, deforestation in South America due to animal feed production. Issues relating to reducing deforestation and forest degradation in developing countries are being addressed as an important and essential part of the solution of the problem of climate change. Deforestation has multiple drivers from different nations and further meaningful efforts to reduce rates of deforestation could be taken based on the principle of 'consumer responsibility.'

Our results illustrate that an equivalent of about 39% of Austria's total carbon emission from domestic livestock production was exported in 2000, and an equivalent of about 22% was imported. This means that Austria's total carbon emissions under the domestic consumption approach comprised only 83% of the emissions accounted under the domestic production approach. If only direct carbon emissions were taken into account, the hypothesis that Austria would embellish its carbon balance by importing emission-intensive products instead of producing them domestically would have to be rejected, at least for the livestock system. The picture changes, however, if land-use related carbon flows are taken into account in the emissions accounting. Our calculations indicate that land-use related emissions are of such magnitude that their inclusion might reverse the overall balance. Carbon emission due to deforestation were 0.3 Mt C/year or about 36% of Austria's domestic emissions in 2000 (about 2.4 kha was deforested in 2000), thus resulting in positive net C emissions of 1.04 Mt C from Austria's trade with livestock-related products versus 0.76 Mt C from Austria's domestic consumption of livestock biomass (Table 5). For reasons of comparison, we quantify the extreme case of emissions from soybeans under conditions of instantaneous deforestation, if the total area (e.g. 42 kha) required for the production of soybean consumed by Austria's livestock had been deforested within 1 year. The resulting carbon emissions would be around 5.5 Mt C in 2000 or more than six fold greater than Austria's carbon emissions accounted under the domestic livestock production approach and would be equivalent to the total carbon emission from Austria's transport sector (e.g. 5.1 Mt C in 2000; UNFCCC (www.unfccc.int)).

The central question investigated here is whether trade-related emissions should be included into the accounting under the KP and whether responsibility sharing should be a key issue in, and part of, a future international climate change regime. In lieu of our study results, it could be argued that Austria should have to compensate Brazil and Argentina financially for the large carbon emissions caused by its imports. As a consequence, land owners in Brazil and Argentina could be financially rewarded for the carbon exported. Such a mechanism would constitute an incentive for expanding cultivation and increasing deforestation. From this perspective, Austria, purchasing the exported carbon, would not be responsible for the GHG emissions resulting from deforestation in South America. However, consumer demand induces a supply with goods. Deforestation in Brazil and Argentina is initiated by the global demand for meat and soybean to which Austria contributes through its domestic consumption. Deforestation represents about 17.4% of the global anthropogenic CO_2-equivalent emissions (IPCC, 2007), where the countries of South America are taking a leading role (Butler, 2005). Conversely, forest net area in European countries — the countries of Annex B of the Protocol and the countries — is increasing (FAOSTAT, 2009). The consumption of soybeans in the EU is continuously increasing (50% of soybeans consumed in the EU is from the Mato Grosso region in Brazil and more than 60% of the total soybean products exported to the EU is produced in Argentina; Greenpeace, 2006; FAOSTAT, 2009). That is we face the awkward situation that the EU (Austria, in our case) can benefit from AR activities within their boundaries as specified under Article 3.3 of the KP but appear at the same time as 'a driving force' or 'responsible' for deforestation that takes place outside their boundaries (mainly in developing countries).

Climate change is an international issue, which requires international cooperation. Activities to reduce anthropogenic GHG emissions from deforestation and fuel combustion in developing countries were elaborated in order to meet the global objective agreed to in the area of climate policy (UNFCCC, 2007; CANA, 2007), namely to reduce global GHG emissions at least 50% below 1990 levels by 2050 and to limit the global average temperature increase by 2 °C (EC, 2007). Based on our study, we argue that this is difficult to achieve by addressing territory-based emissions, i.e., by accounting emissions following a domestic production approach. Some regions, mainly developing countries, can become more carbon-intensive due to decreasing incentives to reduce GHG emissions. In contrast, an accounting principle that focuses on domestic consumption could be considered as a tool that can help to manage carbon flows and develop policies for the reduction of carbon emissions to the atmosphere. A consumption-based indicator could be implemented as a complementary measure to limit emissions in the long-term. However, if a consumption-based principle is followed, this also requires including land-related carbon flows consistently in such an accounting framework. Our study highlights the importance of such an approach due to the magnitude of carbon involved, but also the need for further research aimed at advancing methodological detail and increasing the availability of datasets for applying the domestic consumption approach. Continued emissions inventorying by statistical agencies dealing with data collection and treatment could help to make this approach accurate and applicable in the future and to develop and to implement innovative approaches helping to combat climate change.

Acknowledgements

This article publishes results from research conducted in the context of a project "Carbon household and socioeconomic change" funded by the Austrian Academy of Science and supported by the Forestry Program of the International Institute for Applied Systems Analysis (IIASA). It contributes to the Global Land Project (www.globallandproject.org). The authors are indebted to the Estonian Archimedes Foundation and a grant SF0142497s03 from the Ministry of Education and Science of Estonia. We thank two anonymous reviewers for their constructive comments.

Appendix A

The calculation of direct carbon flows emitted from Austrian production and bilateral trade with livestock products was carried out using the formulas presented below.

A.1. Carbon Emissions from Enteric Fermentation and Manure Management (Figs. 1 and 6)

$$Emissions_{EnF_{ij}} = [EF_{EnF_{ij}} \times pop_{ij} / (10^6 kg / Gg)] \times 12 / 16 \qquad (A1)$$

where, $Emissions_{\mathrm{EnF}i}$ — carbon emissions from enteric fermentation in a specific category of animals i in country j, Gg CH_4/year; $EF_{\mathrm{EnF}ij}$ — enteric fermentation emission factor for the specific category of animals i of country j, kg/head/year (IPCC, 2006); pop_{ij} — the number of animals of specific category i in country j, head/year; and *12/16* — the ratio of the atomic mass of a methane molecule to the atomic mass of a carbon atom, GgC_GgCH_4.

$$Emissions_{MM_{ij}} = [EF_{MM_{ij}} \times pop_{ij} / (10^6 kg / Gg)] \times 12 / 16 \qquad (A2)$$

where, $Emissions_{\mathrm{MM}i}$ — carbon emissions from manure management for a defined population i of animals in country j, Gg CH_4/year; $EF_{\mathrm{EnF}i}$ — manure management emission factor for the defined population of animals i of country j, kg/head/year (IPCC, 2006).

A.2. Carbon Emissions from Livestock Slaughtered for Meat and Milk (Figs. 1 and 6)

In order to estimate emissions from enteric fermentation and manure management from ‘meat and milk’ bilaterally traded, a recalculation of livestock population slaughtered for meat (A3) and producing milk (A4) was performed. The formulas (A1) and (A2) were applied in order to estimate direct emissions from livestock.

$$Slaughtered\_livestock_{ij} = Meat_{ex_{ij}} / Carcass\_Weight_{ij} \qquad (A3)$$

where, $Slaughtered\_livestock_{ij}$ — number of animals of category i slaughtered for meat production in country j, head/year; $Meat_{iexij}$ — values of i meat category exported from country of origin j, kg/year; and $Carcass\_Weight_i$ — average weight of animals of category i slaughtered for meat production in country j, kg/head.

$$Dairy\_Cattle_j = Milk_{ex_j} / Milk\_Yield_j \qquad (A4)$$

where, $Dairy\_Cattle_j$ — number of dairy cattle in country j, which produce milk for export, head/year; $Milk_{exj}$ — value of milk exported from country of origin j, kg; and $Milk\_Yield_i$ — milk yield per cow in country j, kg/cow.

A.3. Carbon Emissions from Meat and Milk Manufacturing (Figs. 1 and 6)

Carbon is emitted due to fossil fuel combusted in the process of meat and milk manufacturing.

$$Emissions_{\mathrm{Manuf}_j} = [Milk / Meat_j \times EF_{\mathrm{Manuf}}] \times 12 / 44 \qquad (A5)$$

where, $Emissions_{\mathrm{Manuf}j}$ — carbon emissions from the manufacturing process in meat and milk production in country j, tonnes C/year; $Milk/Meat_j$ — value of meat and milk exported from country of origin j, kg/year; EF_{manuf} — CO_2 emission rate emitted in the process of meat/milk manufacturing, CO_2 kg/kg of meat/milk; and *12/44* — the ratio of the atomic mass of a carbon atom to the atomic mass of a CO_2 molecule, tC_tCO_2.

A.4. Carbon Emissions from Transportation of Livestock Products (Figs. 1 and 6)

The estimates of emissions from transporting living animals and animal products were evaluated taking into consideration the following assumptions: a distance between a country-exporter to Austria and vice versa was taken as a distance between capital cities of countries. Another assumption was made that products are transported by trucks inside of Europe and by ship, if trade has taken place between Austria and a non-European country.

A.4.1. Carbon Emissions from transportation of living animals

$$Emissions_{\mathrm{TransportLA}i} = [pop_{LA_i} \times Dis_{jd} \times EF_{\mathrm{transp}_{\mathrm{LA}i}} \times (12 / 44)] / 10^9 g / Gg \qquad (A6)$$

where, $Emissions_{\mathrm{TransportLA}i}$ — carbon emissions from transportation of living animals of category i, Gg/year; $pop_{\mathrm{LA}i}$ — number of living animals exported from a country of origin j, head/year; Dis_{jd} — distance between country of origin j and country of destination d, km; EF_{transpLA} — CO_2 emission rate of a vehicle, g/head km; and *12/44* — the ratio of the atomic mass of a CO_2 molecule to the atomic mass of a carbon atom, gC_gCO_2.

A.4.2. Carbon Emissions from transportation of animal products

$$Emissions_{\mathrm{TransportAP}} = [Meat / Milk \times Dis_{jd} \times EF_{\mathrm{transp}_{\mathrm{AP}}} \times (12 / 44)] / 10^9 g / Gg \qquad (A7)$$

where, $Emissions_{\mathrm{TransportAP}}$ — carbon emissions from transportation of animal products, Gg/year; *Meat/Milk* — value of meat/milk exported from a country of origin j, tonnes/year; and $\mathrm{EF}_{\mathrm{transpAP}}$ — CO_2 emission rate of a vehicle, g/t km.

A.5. Carbon Input via Feed Intake and the Land Area Requirements (Figs. 1 and 6)

In order to estimate carbon input via feed intake by living animals and by ‘meat and milk,’ a recalculation of livestock population slaughtered for meat and producing milk was carried out. Livestock nutrition diet varies from one region of the world to another, thus feedstuff mix (as a share of each feedstuff in the total feed use — e.g. market feedstuff, non-market feed, by-products and grazing) for each region was applied in the estimates (Wirsenius, 2000; Krausmann et al., 2008).

$$CI_{ij} = pop_{ij} \times GEI_{ijy} \times CF_y \times CC \times 10^{-6} kg / Gg \qquad (A8)$$

where, CI_{ij} — carbon input via feed intake by animal of category i in country j, t C/year, Gg; pop_{ij} — number of animals of category i in country j; GEI_{ijy} — gross feed intake of animal feed of category y by animal of category i in country j, kg FM (fresh matter)/head/year; CF_y — conversion factor from fresh matter to dry matter of animal feed of category y, kg FM/kg DM (employed from Jonas and Nilsson, 2001); and CC — carbon content (an average value 0.5), kg C/kg DM.

The data on harvest index reported in the FAO dataset and gross energy intake for all types of animals (total kg FM/year) were taken into account in order to estimate land requirements for feedstock production (A9).

$$Land_{ijy} = GFI_{ijy} \times HI_y \qquad (A9)$$

where, $Land_{ijy}$ — land area requirement in country j for production of feed category y for animal category i, ha/year; GFI_{ijy} — gross feed intake of feed category y by animal of category i in country j, t FM/head/year; and HI_{jy} — global average harvest index of animal feed category y, t FM/ha.

Appendix B

B.1. Calculation Example: Land Requirement in Brazil for Soybean Cultivation Imported to Austria through Germany

In order to estimate ‘hidden carbon flows’ emitted from soybean cultivated in Amazonia and exported to Austria through Germany a

Table B1
Soybean flows in Germany in 2000, tonnes.
FAOSTAT, 2005.

	Production, tonnes	DMI, tonnes	Production/DMI	Import/DMI
Germany	1000	3,841,424	0.03%	
Argentina				1.5%
Brazil				32.4%
The Netherlands				35.4%
The USA				30.3%

Table B2
Soybean flows of The Netherlands in 2000, tonnes.
FAOSTAT, 2005.

	Production, tonnes	DMI of soybeans	Production/DMI	Import/DMI
The Netherlands	–	5,381,490	0%	
Argentina				2.1%
Brazil				*47.3%*
The USA				46.0%

calculation algorithm developed on the basis of the scheme in Fig. 4 was employed. The data for 2000 was used in the estimates.

An import/production ratio of soybean in Brazil was only 0.025, the import was mostly from Paraguay and Argentina in 2000. Brazilian export of soybeans made up 34.3% of DMI in 2000 (B1). 62% of DMI was taken for the manufacture of soybean oil and soybean cake.

$$DMI_i = P_i + \mathrm{Im} \tag{B1}$$

where, DMI_i — domestic material input of country *i*, tonnes/year; P_i — soybean production in country *i*, tonnes; and *Im* — import of soybeans to a country *i* from country of origin, tonnes/year.

DMI was 3841 thousand tonnes of soybeans in Germany in 2000, a ratio of import to DMI was 99.9% (Table B1). More than 33% of the import of soybeans was import of soybean cake and 67% — soybeans. Brazil is one of main exporter-countries of soybeans (incl. soybean cake and soybean oil) to Germany, along with The Netherlands and the USA (Table B1).

It is important to note that The Netherlands does not produce soybean, the country just re-exports soybeans from other countries: mostly from Brazil and the USA (Table B2). A sub-flow of soybeans from The Netherlands was taken into consideration. Export of soybeans to the USA was negligible, 0.2% from the total amount produced.

Soybean is used mostly for soybean cake manufacturing, which is fed to livestock. Therefore, we focused our attention mainly on soybean cake product. More than 96% of the DMI of soybean was used for processing in Germany (Table B3). The total amount of soybean cake produced in Germany was 2963 thousand tonnes (80% of the total amount of soybeans consumed). Taking into account the 'efficiency' of soybean cake production and amounts of soybeans imported and used for soybean cake manufacturing we calculated quantities of soybean cake produced from imported soybeans (B2, column D of Table B3).

Table B4
Import of soybean cake to Austria from a country-producer through Germany, tonnes.

Country of origin	Soybean cake, tonnes
Argentina	17,044
Brazil	41,556
The Netherlands	51,746
…from Brazil	*24,120*
The USA	25,486
Total	110,347

Table B5
Land required for soybeans production (consumed in Austria) in Brazil, Argentina and USA, ha.

Country	Soybeans used for soybean cake production, tonnes	Harvest index, t/ha[a]	Area required for soybean cultivation, ha
Argentina	21,238	2.34	9076
Brazil	51,782	2.4	21,576
The Netherlands	64,480		
…from Brazil	30,056	2.4	12,523
The USA	31,757	2.56	12,405

[a] FAOSTAT, 2005.

$$SoyCake = \mathrm{Im}_i \times Manuf\,,\% \times Ef\,,\% \tag{B2}$$

where, Im_i — import of soybean from country *i*, tonnes/year; *Manuf,%* — ratio of soybean used for processing to DMI, %; and *Ef,%* — efficiency of soybean cake production from soybean, %.

The total amount of soybean cake imported directly and produced in Germany was 4852 thousand tonnes (column D plus column E of Table B3).

A ratio of soybean cake imported to Germany (directly and indirectly) from a producer-country is illustrated in Table B3 (column G), the values were estimated using the formula (B3).

$$Soy\,Cake_i = (SoyCake_{\mathrm{prod}} + Soy\,Cake_{\mathrm{im}})\,/\,\sum Soy\,Cake_{\mathrm{prod,im}} \tag{B3}$$

where, $SoyCake_i$ — value of soybean cake imported from country *i* (directly and indirectly) tonnes, %; $SoyCake_{\mathrm{prod}}$ — amount of soybean cake produced from soybean imported from country *i*, tonnes/year; and $SoyCake_{im}$ — value of soybean cake imported from country *i*, tonnes/year; Amounts of soybean cake imported to Austria from a country-producer of soybean were evaluated using the formula (B4).

$$Soy\,Cake_{\mathrm{Austria},j} = Soy\,Cake_{\mathrm{Austria}_{im_i}} \times Soy\,Cake_j, \% \tag{B4}$$

where, $SoyCake_{\mathrm{Austria}i}$ — import of soybean cake to Austria from country-producer *j* through Germany, tonnes/year (Table B4); $SoyCake_{\mathrm{Austria}j}$ — total import of soybean cake to Austria from country *i* (Germany), tonnes/year; and $SoyCake_i$,% — ratio of soybean cake

Table B3
The estimation of the total soybean cake input to Germany from a country-producer.

	Used for manufacture of soybean cake, tonnes	Used for manufacture / DMI (%)	Soybean cake produced from imported soybeans, tonnes	Soybean cake import (directly), tonnes (FAOSTAT, 2005)	Soybean cake imported by countries, %
A	B	C	D	E	F
Germany	3,693,000	96.1%			
Argentina			45,837	554,641	12.4%
Brazil			960,330	503,729	30.2%
Netherlands			1,049,016	774,049	37.6%
…from Brazil			*495,731*	*354,051*	*17.5%*
USA			897,877	3	18.5%

imported to Germany from a country-producer *j* of soybean (column F of Table B3), %.

In order to estimate land required for cultivation of 'soybean cake' imported to Austria through Germany, inverse calculations were applied. The amounts of soybean cake imported were recalculated to soybean using the efficiency of soybean cake production. The amounts of soybean were divided by harvested index of soybean (Table B5). As result, the total area required for soybean production consumed by Austrian livestock, was 55,581 ha, where 43,175 ha was area cultivated in Brazil and Argentina (Table B5).

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PUBLICATION II

O. Gavrilova, R. Vilu, L. Vallner. A life cycle impact assessment of oil shale produced and consumed in Estonia. *Resources, Conservation and Recycling* 2010, 55, 232–245.

Resources, Conservation and Recycling 55 (2010) 232–245

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

A life cycle environmental impact assessment of oil shale produced and consumed in Estonia

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ARTICLE INFO

Article history:
Received 28 January 2010
Received in revised form
30 September 2010
Accepted 30 September 2010

Keywords:
Oil shale
Life Cycle Inventory
Material Flow Analysis
Estonia
Electricity and heat generation
Shale oil production

ABSTRACT

With 0.5–1.0% of the world's oil shale reserves, Estonia mines more than 48% of the total world oil shale output. Electricity, thermal energy and shale oil are produced from oil shale in Estonia. Enterprises operating on oil shale have been the main polluters in Estonia for several decades. A comprehensive quantitative analysis of the pressure on the environment and efficiency of the oil shale complex was carried out using Life Cycle Inventory and Material Flow Analysis methodologies. The results of this study are relevant to the implementation and further development of oil shale resource policies.

1. Introduction

During the last 95 years, oil shale, a sedimentary rock containing combustible organic matter, has played a vital role in the Estonian economy. Over 1.6 billion tonnes (1.6×10^9 t) of oil shale (one third of the total national reserve) have been extracted in Estonia since 1916 (ESO, 2003; Kattai et al., 2000), and Estonia remains a leading producer of oil shale in the world. With 0.5–1.0% of the world's oil shale reserves, Estonia mines more than 48% of the total world oil shale output (Laherrere, 2005) and uses it for electricity and thermal energy (i.e., heat) generation, shale oil production (i.e., a synthetic crude oil produced by retorting of oil shale), as well as in the process of cement production (as fuel for clinker oven). In total, the Estonian oil shale complex (hereinafter referred to as "the complex") consists of four branches and thirteen facilities. The complex accounts for 4% of the Estonian gross domestic product, employs 7500 people, equal to 1% of the national employment (ESO, 2009), and is responsible for generating the majority of wastes polluting air, water and soil in Estonia. The production and consumption of oil shale will continue in the future (KKM, 2009), leading to a further increase of the negative burden on the environment in Estonia.

A number of research projects have investigated the oil shale resource itself, the technological processes related to oil shale use and the impact on the environment associated with these processes (ELF, 2006). However, these studies have focused each on only one or a few of a large number of issues associated with the extraction and consumption of oil shale, so they have not offered a complete, integrated and comprehensive overview and analysis of oil shale processing or environmental pressures involved. We therefore lack the context necessary to make well-informed decisions about the possible futures of oil shale complex in Estonia.

The broad goal of the present study is to assess the overall pressure on the environment associated with the entire life cycle of oil shale resource use, with a special emphasis on the efficiency of resource utilisation. This type of comprehensive, detailed and stepwise analysis of oil shale life cycle is the first for Estonia. The results of the Life Cycle Inventory (LCI) and Material Flow Analysis (MFA) are presented herein.

2. Methodology

The general procedures of the LCI and MFA were used to achieve the goal set up in this study: to examine efficiency of oil shale resource use throughout its life cycle and associated environmental pressures (i.e., pollution emissions, deposition of final waste, extraction of resources and land transformation).

The LCI is one of the phases and its results—primary input for conducting life cycle assessment (LCA) of a product (ISO 14040,

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doi:10.1016/j.resconrec.2010.09.013

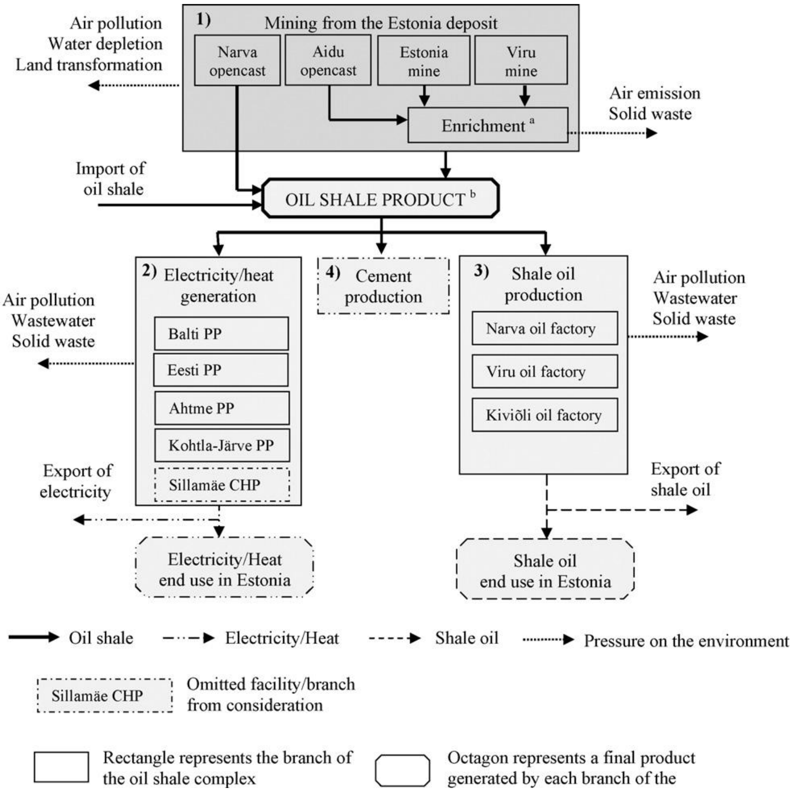

Fig. 1. Flow diagram for the life cycle of oil shale produced and consumed in Estonia. [a]Oil shale mix with limestone (see Section 3.2.1). [b]Quantity of oil shale stored in stock at the beginning of year was taken into account.

2000; Guinée et al., 2002). By compiling the LCI inventory, we aimed to provide reliable and comprehensive information on environmental pressures exerted throughout the oil shale life cycle, which would allow to evaluate environmental impact of each stage (or branch and facility), would show the greatest potential for the environmental improvements and would help to make better-informed decisions concerning the further use of the oil shale resource. The LCI inventory was compiled in four major steps: (1) determination of the assessment scope and boundaries; (2) appraisal of data quality; (3) assessment of inventory output; and (4) interpretation of inventory results.

The MFA is a tool that can provide a holistic view of energy, material and resource flows in a well-defined system (e.g., industrial complex, national economy, etc.) (Eurostat, 2001). In other words, the MFA provides a logical basis for the physical book-keeping for energy, material and resource flows—for the comprehensive recording of input, output and accumulation or losses of them. In our study, we focused on the oil shale resource input flow and oil shale-based products' output flows (i.e., electricity, heat and shale oil) within each branch of the oil shale industry. Hence, by employing the MFA, we evaluated the efficiency of primary energy use (i.e., oil shale) in the production of secondary forms of energy—electricity, heat, shale oil (i.e., energy-recovery ratio).

2.1. Scope and goal of the study

The goal of this study was to appraise the efficiency of oil shale energy use in each branch/facility of the complex, and to assess the environmental pressures caused through the entire life cycle of oil shale in Estonia, including mining and consumption for electricity and heat generation, as well as shale oil production. This goal comprises several specific objectives that will allow us to assess the interaction between the oil shale complex and the environment:

- to assess environmental pressure per functional unit of product generated (i.e., gigajoule (GJ) of oil shale, electricity, heat and shale oil) per year, as well as the cumulative pressures on the environment accumulated since the commencement of oil shale mining and use during the entire life cycle;
- to identify the main polluting branch (or facility) of the complex and to characterise the specific aspects of oil shale resource use that lead to negative impact on the environment;
- to provide readily understandable, consistent and transparent data on the efficiency of the oil shale extraction process and of the energy-recovery ratio of oil shale use in all branches of the complex suitable also for comparing of the overall efficiency of the branches.

The scope of this study included aspects related to the entire life cycle of oil shale, from raw material extraction and refining to combustion and processing. We employed a simplified approach to investigate emissions into the environment from facilities (i.e., facility level). However, in case of shale oil production technology-based assessment was used.

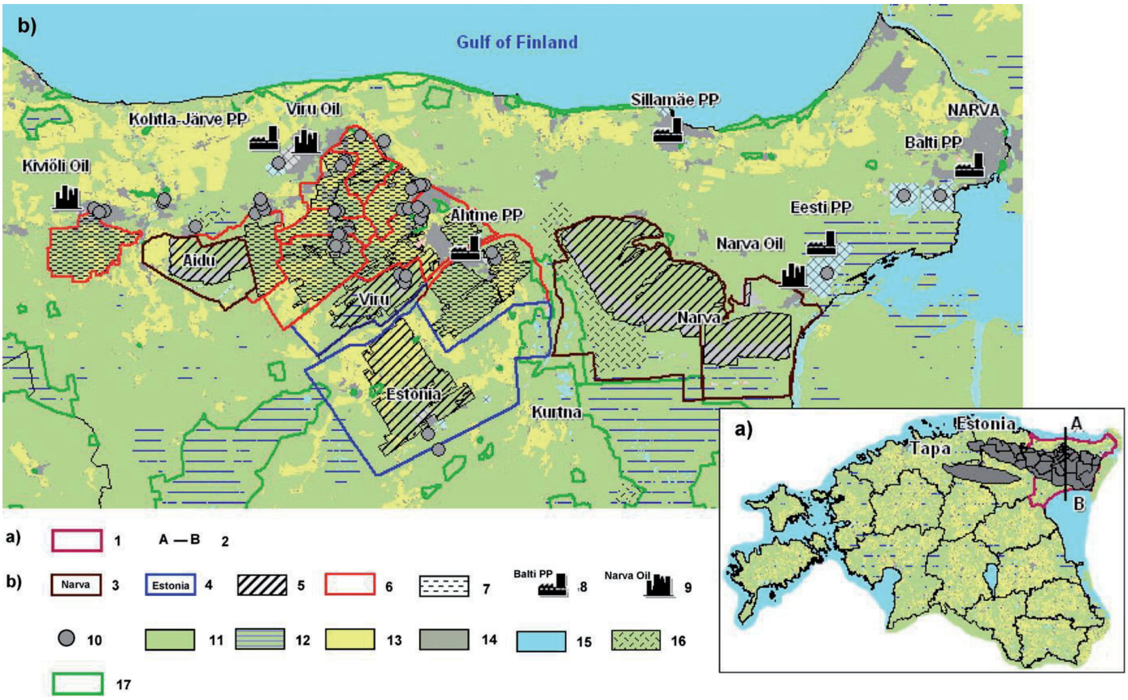

Fig. 2. Location of oil shale deposits, facilities of the complex producing and consuming oil shale, and waste disposal sites as of 2002. (a) Location of oil shale deposits: Estonia, Estonia oil shale deposit; Tapa, Tapa oil shale deposit; 1, border of Ida-Viru County; 2, line of hydro-geological cross-section (see Fig. 3); (b) Facilities of the oil shale complex: 3, border of opencast mine in operation; 4, border of underground mine in operation; 5, mined-out area; 6, border of closed mine; 7, exhausted and flooded area; 8, electricity and heat generation power plant; 9, shale oil producing factory; 10, waste disposal site. Land cover: 11, forest land; 12, wetland; 13, agricultural land; 14, built-up area; 15, water body; 16, peat extraction area. General: 17, border of nature reserve; Kurtna, Kurtna Landscape Reserve; NARVA, town.

2.2. *System boundaries*

The system boundaries of the entire oil shale life cycle studied are depicted in Fig. 1. The flow diagram visualises all the major branches of the oil shale complex as follows: (1) oil shale resource mining (including the enrichment stage); (2) oil shale-based electricity and heat generation; (3) oil shale retorting (i.e., shale oil production); and (4) oil shale combustion in the process of cement production (referred as “Cement production” in Fig. 1). The latest was not analysed because of the insignificant volume of oil shale consumed in the process (i.e., 3% of the total quantity of oil shale consumed) and tangled technological process of cement production. Import and export of oil shale and related products were included in the analysis. The emissions to the environment from oil shale transportation were ignored in the study because of a lack of available data.

The study focused on twelve facilities in the complex, given as follows (Fig. 2): (1) four oil shale mining facilities, including the enrichment plants (all operated by Eesti Põlevkivi Limited (hereinafter referred to as “EP Ltd.”)), a subsidiary of Eesti Energia Ltd. (hereinafter referred to as “EE Ltd.”); (2) four power plants (PPs): Balti, Eesti, Ahtme and Kohtla-Järve, all owned by EE Ltd. Emission flows associated with Sillamäe CHP operating on oil shale were omitted because of a lack of available data and the small volume of oil shale used; and (3) three shale oil factories: the Narva, Viru and Kiviõli oil factories (operated by EE Ltd., Viru Keemia Grupp Ltd. and Kiviõli Keemiatööstus Ltd., respectively). All facilities are located in Ida-Viru County in the northeastern part of Estonia (Fig. 2).

2.3. *Functional units*

The choice of unit (i.e., functional unit) for measuring and describing products and processes in the LCI is an important aspect of the analysis. Despite the common functional unit accepted and defined by the performance or services of the functional outputs of a product system delivered to customers (ISO 14040, 2000), the functional unit chosen for this study was the energy value in GJ of the final product generated by each branch of the complex (i.e., oil shale, oil shale-based electricity, heat energy and shale oil). Reference flows (i.e., input and output flows), which enable the products to be treated and compared with alternative products of the product market (e.g., coal-based electricity and heat, crude oil) were limited by considering only input and output flows associated with the environment (i.e., pollution emissions into air, water and generation of waste, surface- and underground water extraction and land transformation), input flows required for the process operation (e.g., chemicals and other materials, equipment, etc.) were omitted from the study. However, we went beyond one of the limitations of the LCI method, which usually do not address localised (spatially defined) pressures on the environment, by identifying and assessing spatial pressure of a branch/facility in a specific region (Guinée et al., 2002). And we also considered annual pressures on the environment which allowed to assess the contribution of a facility/branch to the total pollution in Estonia. Cumulative environmental pressures of the facilities (or the branches) accumulated since the commencement of their operation, i.e., the incremental environmental pressures from the past and the present were included and assessed. The evaluation of the

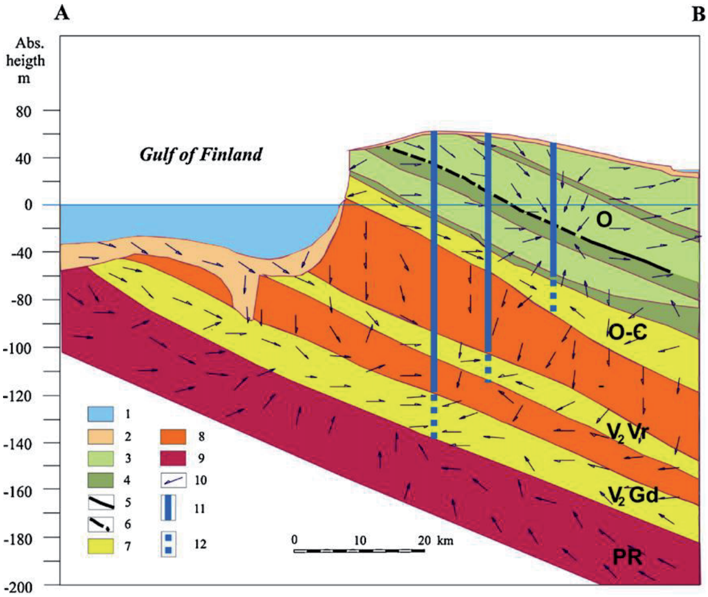

Fig. 3. Hydro-geological cross-section of northeast Estonia. 1, Saline sea water; 2, Quaternary deposits (till, sandy loam, silt); Ordovician carbonate rocks: 3, aquifers (limestone, dolomite); 4, aquitards (marl, clayey limestone); 5, oil shale bed; 6, mined-out area of underground oil shale mine. Ordovician, Cambrian and Vendian clastic and argillaceous rocks: 7, sandstone aquifers; 8, clayey aquitards; 9, Crystalline basement; 10, groundwater flow direction; 11, production well; 12, well screen. Groundwater bodies: O, Ordovician; O-Є, Ordovician-Cambrian; V_2Vr, Vendian Voronka; V_2Gd, Vendian Gdov; PR, Precambrian.

cumulative pressure allowed to understand and address a scale of the environmental changes occurred in the region because of the operation of the complex. Focusing on the cumulative pressure is especially important in evaluating changes of land topography and hydro-geological balance and water quality of the region due to the operations of the facilities of the complex, and land use changes and contamination of the surrounded environment due to the waste disposal.

Applying a product-based energy unit makes the analysis more transparent and comparable within the complex. Furthermore, the unit chosen will allow the LCI user to compare reference flows per GJ of other products generated in other (not-oil-shale industries), e.g., GJ of brown or hard coal produced, GJ of electricity or heat generated from coal or gas, or GJ of residual fuel oil produced, or to clarify the overall environmental burden associated with the GJ of oil shale-based electricity and heat generated, as well with shale oil produced. In other words, it allows the LCI user to 'link and embed' a portion of the pressures that occur in the process of oil shale mining to the environmental pressures caused by the generation of oil shale-based electricity and heat (via amount of oil shale consumed). This also allows to connect a share of the pressures associated with oil shale mining and oil shale-based electricity and heat generation to the environmental pressures associated with shale oil production (via the amount of oil shale and quantity of electricity and heat consumed).

More specifically, this paper was assembled and structured in conformity with the following types of reference flows: (i) pollution emissions into air and water, water resource extraction, solid waste generation and land transformation (i.e., the environmental pressure) per GJ of products generated (i.e., oil shale, electricity and heat, and shale oil); (ii) annual environmental pressure; and (iii) cumulative pressure on the environment localised in space from the operation of oil shale facilities.

The energy-recovery ratio of oil shale use (i.e., the efficiency of oil shale energy conversion to final products: electricity, heat and shale oil) in the various branches of the complex was evaluated based on energy flows measured in GJ.

2.4. Inventory data

Data from 2002 were used to estimate the environmental pressure per GJ of product(s) and annual flows for the sake of completeness. Additionally, data of 2001 and 2006 were employed in some specific cases to explain and justify choosing the most appropriate data (see Section 3.2.2.2) or to demonstrate emission alterations due to important technological changes and environment protection activities introduced (see Section 3.2.2.1). Data of 2007 were used, as the best available, to evaluate the pressure of oil shale mining on water resource (refer to Section 3.2.1.4).

Data were collected and adjusted from primary and secondary data sources as follows: (1) amounts of oil shale extracted, emissions into air and water, waste generation and water use by each mining facility (in tonnage) were obtained from the environmental department of EP Ltd. The department quantifies emission data based on estimations and measurements. In particular, emissions into the air from boiler-houses or blasting operations are estimated based on the quantity and quality of fuels consumed and on the quantity of explosive consumed, according to a procedure to determine ambient air pollution levels (KKM, 2004; State committee of the USSR, 1986). Emissions into water are estimated on the basis of the measurements of concentrations of pollutants in water and annual wastewater flow. Quantities of water pumped out in the process of mining are estimated based on the capacity of the pumping plant and its operational time (i.e., according to a procedure determined for water use) (KKM, 2002). The amount of extracted oil shale is calculated based on a surveyor methodology (i.e., a coefficient of dilution is not taken into account). Emissions and the quantity of resources used (i.e., oil shale and water pumped out), obtained from EP Ltd. and employed in the study, are a basis for environmental taxation and charges and carefully examined by

Ministry of the Environment—this certainly increases accurateness and reliability of the data.

(2) Data related to the operation of the PP generating oil shale-based electricity and heat in 2002 were obtained from a high-quality reliable primary source: annual reports published by EE Ltd. These reports covered all types of the environmental pressure that occurred during the operation of all PPs (i.e., pollution emissions into air, water, waste generation and water extraction), as well as the amount of oil shale consumed and electricity and heat generated. Emissions and waste are quantified based on measurements in the facilities, according to the procedures established (KKM, 2002, 2004), and are also a basis for environmental taxation and charges. Data on electricity and heat generation reported by EE Ltd. (EE, 2002) were consulted and supplemented with energy balance data (ESO, 2003) to ensure data quality.

To estimate and provide changes in pollution emissions into air per GJ of product from the PPs, because of the important technological changes in oil processing technology and the launching of more efficient environment protection initiatives in 2005, secondary data sources were used. Since EE Ltd. changed their method of data reporting in 2003, the later data presented in the study could be considered less reliable.

(3) The investigation of the pressure of shale oil production facilities on the environment was based on the analysis of technologies (instead of the analysis of operation of facilities) to ensure the quality of the results. In particular, the data necessary for the analysis and the evaluation of shale oil production processes were not provided by the facilities (i.e., the primary data source), but were reported in national statistics (EEIC and ESO), which made it essentially impossible to perform a detailed analysis. For example, Kiviõli Oil reported that air emissions of the whole complex included emissions from a PP producing heat and steam for technological processes and for inhabitants of a nearby town. This meant that the values of emissions, etc. per GJ of shale oil produced would be overestimated. Data from the secondary data sources were considered to be the best available in these situations because the data were based on long-term research expertise (e.g., Soone et al., 2004; Yefimov, 2000). Data on the quantity of oil shale consumed to produce shale oil and the quantity of shale oil produced by a facility were found in reliable data sources (EE, 2003; MKM, 2003; VKG, 2009).

More than 200 reports and scientific articles were referenced to evaluate reliably the cumulative pressure on the environment caused by the long-term operation of the facilities of the complex.

3. Results

3.1. The oil shale resource

The scientific name of Estonian oil shale is kukersite, and it contains organic, carbonate and terrigenous components. The latter two components constitute mineral matter, whereas organic matter content varies from 10 to 65% (Kattai et al., 2000). Oil shale occurs as seams in Ordovician carbonate bedrock in Estonia (Fig. 3). There are two principal oil shale deposits in Estonia: Estonia and Tapa (Fig. 2) (Kattai et al., 2000).

The area of the Estonia deposit is about 3000 square kilometers (km^2). The calorific value of the commercial seam of oil shale (i.e., kukersite beds with limestone interlayers) is highest in the northern part of the central and the eastern area of the deposit—from 9.0 to 10.5 GJ per tonne (GJ/t) (the thickness of the oil shale seam is in the range of 2.7–2.9 meters (m)), corresponding to the calorific value of kukersite seams (i.e., without limestone interlayers) of 12.5–13.5 GJ/t. The value is lower towards the southern and the western parts, down to 5.0–7.5 GJ/t (thickness of the seam at 1.4–2.6 m) (Fig. 2). The total dry matter density of all beds varies from 1.2 to 1.8 tonne per cubic meter (t/m^3) (Kattai et al., 2000).

The total oil shale reserve (i.e., proved and possible resource, defined according to the classification of a level of geological exploration) of all the fields of the Estonia deposit is estimated to be 8.7 billion tonnes (8.7×10^9 t) (KKM, 2009). The oil shale resource is classified also according to ecological and economic profitability, and the energy rating of oil shale beds (GJ per square meter (GJ/m^2)) is chosen to be a measure of profitability. The resource is classified as active when the energy rating of oil shale seam is at least 35 GJ/m^2, and it is passive when the rating is 25–35 GJ/m^2. The oil shale reserve, based on an economic profitability classification, is about 5.0×10^9 t, where 1.5×10^9 t are classified as active and 3.5×10^9 t are passive (Valgma, 2003). About 4% of the total oil shale active reserve is located under built-up areas (Kattai et al., 2000). To date, more than 40% of the oil shale bed with an energy rating of 48–35 GJ/m^2 and 0.1% with a rating lower than 35 GJ/m^2 have been extracted (Valgma, 2003).

The reserves of the Tapa deposit (2.6×10^9 t) have not yet been extracted. Seam thickness there varies from 1.0 to 2.0 m, with an average energy rating of 6.1 GJ/t. The area of the Tapa deposit is 1150 km^2 (Kattai et al., 2000).

3.2. Oil shale production and consumption

About 13 million tonnes (13×10^6 t) of commercial oil shale was consumed in Estonia in 2002 which included 0.7×10^6 t of oil shale imported from Russia. Of this figure, 80% (with an average calorific value of 8.3–8.7 GJ/t) was used for electricity and heat generation, about 17% (with a calorific value of 8.5 GJ/t or 11.3–11.8 GJ/t, depending on technology) was consumed for shale oil production, and the rest was used in the cement industry (ESO, 2003; Kattai et al., 2000). Oil shale use increased to 15×10^6 t by 2007 (ESO, 2009), but the structure and technologies of use have not changed significantly from 2002 unless specifically indicated in the text.

3.2.1. Oil shale mining and enrichment

Oil shale mining is performed in Estonia using a surface method (i.e., opencast, at a depth of 5–20 m) as well as an underground method (20–70 m deep). Full-face and partly selective methods are used in the Aidu and Narva opencast mines, but the room-and-pillar method is used in the underground mines in Estonia and Viru (Fig. 2).

The next to mining stage in the industrial chain of on-site oil shale processing is enrichment, which means separating the particles of limestone from oil shale. This process increases the energy value of extracted oil shale and proceeds as follows: the raw mix of oil shale and limestone extracted is crushed and directed to enrichment factories. Before the enrichment process, lumps of the raw mix are screened out. In the result of the process, fine-grade lumps (smaller than 25 mm) of oil shale are sold without the enrichment and small lumps of bigger than 25 mm in size are enriched in large suspension baths, where the heavier limestone lumps sink to the bottom and the lighter oil shale floats. The limestone lumps are classified as the enrichment waste (i.e., waste rock) and transported to waste heaps. The enrichment process, established at underground mines and at the Aidu opencast mine, generates about 4×10^6 t of solid waste annually (see Section 3.2.1.3). Formerly, oil shale losses in the enrichment process were 3–6% of the total quantity of extracted oil shale (Puura, 1999; Reinsalu, 1988); improvements in the technology of enrichment process have decreased the losses of the resource recently (Puura, 1999). However, due to the lack of data on oil shale losses in the enrichment process (in tonnage and energy terms) in 2002, the analysis of that stage of the process was omitted from the study of the efficiency of oil shale energy use; this fact increased the energy-recovery ratio of oil shale use in

Table 1
Production of oil shale and losses of the resource in the process of mining in 2002, 10^6 t [10^6 GJ] (calculated based on survey measurement; EP, 2003).

Mine	Oil shale production	Oil shale losses	Oil shale reserved used
Viru mine	1.63	0.57	2.20
Estonia mine	3.99	1.67	5.65
Narva opencast	3.36	0.39	3.76
Aidu opencast	1.54	0.67	1.60
Total	10.51 [111.10][a]	2.69 [28.42]	13.66 [139.52]

[a] The quantity of oil shale extracted and the resource losses in energy output terms (i.e., in 10^6 GJ) were calculated taking into account the data reported by EP Ltd. (EP, 2003) on the amount of oil shale mined out in tonnage output terms, the coefficient of dilution and the average calorific value was adjusted from energy balance (ESO, 2003).

Table 2
Land resources of Ida-Viru County "disturbed" by mining operations as of 2002 in km^2 (Kattai et al., 2000; ESO, 2009).

	Area
The area of Ida-Viru County	3,364
Mined-out area	423.9
. . .by underground method	283.9
. . .by opencast method	140.0

'electricity and heat generation' and 'shale oil production' branches (refer to Sections 3.2.2 and 3.2.3). Nevertheless, the pressure on the environment due to the enrichment process was included in the inventory.

Net production of commercial oil shale (i.e., oil shale product) was 12.4×10^6 t or 111.10×10^6 GJ in Estonia in 2002 (ESO, 2003; EP, 2003). It differs from 10.5×10^6 t reported by EP Ltd. (Table 1) which was based on survey measurements, where a coefficient of oil shale dilution was not taken into account. Of the resources, 46.6% was procured at the Aidu and Narva opencast mines, and 53.4% came from the Estonia and Viru underground mines. The percentage of oil shale resources lost in the process of mining, compared to the total amount of oil shale reserve used in the process, was 20.4% (i.e., 4–10% in opencast mines: Aidu and Narva, respectively and 25–30% in underground mines: Viru and Estonia, accordingly (Table 1)). However, Kattai and Kattai (1971) argued that annual losses add up to 30% if one considers also oil shale reserves in mining areas, which were written-off because of difficult hydrogeological and geological formations impeding the exploitation of the resource. Hereinafter, however, our estimations were based on oil shale losses reported by EP Ltd. (2003).

3.2.1.1. Pressure on land resources. About 28 GJ (if the resource with an energy rating of 35 GJ/m^2 is being mined) can be produced from 1 m^2 of the deposit; then about 4 km^2 of land is transformed into "disturbed mined-out land" annually in the result of oil shale mining operations. The total mined-out area was 424 km^2, which comprised 12.6% of Ida-Viru County territory in 2002 (Kattai et al., 2000). About 8.4% of the county's area had been "disturbed" by mining using the underground method and 4.2% had been "disturbed" by the opencast methods (Table 2 and Fig. 2). Both surface and underground mining methods influence the topography of region and change the soil productivity and lead to subsidence of land surface area. About 87 km^2 of the area "disturbed" by the underground method was classified as subsided where the relief was changed in the result of the failing of underground pillars, 36 km^2 was defined as stable and 150 km^2 was defined as unstable, 79% (72.4 km^2) of which was liable to subside in the coming decades (Reinsalu et al., 2002). Since 2002, the total area of land disturbed by opencast and underground mining operations has expanded by about 24 km^2, which has exacerbated the impact of oil shale mining on land topography in the region.

3.2.1.2. Emissions into air. Sources of emissions into the atmosphere associated with mining and enrichment operations include the following: blasting, loading and crushing; enrichment activities (including screening-out process); and combustion emissions from diesel-powered equipment as well as from administrative utilities. Boiler-houses of mines are the main sources of atmospheric emissions in the extraction stage. Blasting operations and oil shale enrichment factories pollute the air with CO, dust and NO_2. Mäetehnika Ltd. (a facility specialising in the maintenance of mining equipment) also emits heavy metals into the air (Table 3). However, emissions from oil shale mining facilities contribute only a small fraction of Estonia's total annual emissions, namely 0.5%, 0.2% and 0.5% of the total SO_2, NO_x and CO emissions, accordingly (EEIC, 2009; ESO, 2009).

3.2.1.3. Solid waste generation. Two major types of solid wastes are generated in the process of oil shale mining and enrichment: a covering layer (i.e., overburden) and solid waste containing limestone originating from the layers intercalating the kukersite beds (i.e., waste rock).

An average coefficient of the overburden removed at the opencast mines is 0.36 m^3/GJ of oil shale produced (Kikas, 1988). Material is temporarily stored off-site and re-used in the restoration operations of opencast mines (Kikas, 1988).

About 35.5×10^{-3} t of waste rock (classified as non-hazardous waste (EU Directive, 1999)) is separated per GJ of oil shale product generated in the process of raw oil shale enrichment and is stored in heaps. About 50% (4×10^6 t) of the total annual volume of non-hazardous solid waste generated in Estonia is produced in Ida-Viru County by oil shale mining facilities (KKM, 2003). From the 1960s to 2002, the total accumulated volume of solid waste (i.e., waste rock) from oil shale mining was 165×10^6 t, which was stored in 33 heaps (pyramidal cones with steep slopes and large height) that covered an area over 3.4 km^2 (Sørlie et al., 2004). Besides of limestone waste, the waste rock contains oil shale separated from rock, and pyrite (Puura, 1999; Kattai and Kattai, 1971). The latter two components and the waste storage technology employed increased

Table 3
Air pollutant emissions from oil shale mining branch in 2002, 10^{-6} t/GJ of oil shale produced (calculated based on EP, 2003).

Polluter	Boiler-house	Blasting operations	Load-crushing complex	Enrichment factories	Mäetehnika Ltd.	Total
Ash	6.77					6.77
Nitrogen dioxide (NO_2)	0.52	0.06			0.01	0.59
Sulphur dioxide (SO_2)	3.88				0.002	3.89
Carbon monoxide (CO)	6.30	2.02			0.04	8.36
Dust		1.32	0.02	0.02	0.05	1.36
Volatile organic compounds (VOC)					0.0005[a]	0.0005
Lead (Pb)					0.00002	0.00002
Vanadium (V)					0.00001	0.00001
Zinc (Zn)					0.000005	0.000005

[a] Emissions of VOC, Pb, V and Zn are low compared to other pollutants, therefore high precision in reporting of emission values was applied.

the risk of self-igniting of heaps. 27% of all heaps (i.e., 9 heaps) self-combusted between 1960 and 1980, and the average burning period was about ten years (Puura, 1999; Sørlie et al., 2004). The leachate of burning/burned heaps contaminated the surrounding surface and groundwater with phenols (Kupits et al., 2004). However, improvements in oil shale enrichment and waste rock disposal technologies after 1980 have significantly reduced the self-ignition of heaps.

3.2.1.4. Pressure on water resources. Mining operations always result in disturbed hydrological characteristics affecting surface run-off, groundwater flow, and water quality.

Overexploitation of underground water resources: To keep mines dry, the karstified Ordovician carbonate bedrock containing oil shale seams must be drained (Fig. 3). To produce a GJ of oil shale, 1.6 m^3 of water (on average) must be pumped out per GJ of mined oil shale (i.e., 1.0 m^3 and 1.5 m^3/GJ from underground mines for Viru and Estonia, respectively, and 1.5 m^3 and 2.8 m^3/GJ from open-cast mines for Narva and Aidu, respectively). In 2007, the total amount of mine water pumped out, treated in sedimentation ponds and directed into the region's river network was 185 million m^3 (185×10^6 m^3 versus 160×10^6 m^3 in 2002) (EP, 2003). This was 3.6 times the amount of groundwater consumed during the same period by the rest of the entire country (Perens and Savva, 2007, 2008). As a result of continuous mine dewatering, the groundwater head decreases along the perimeter of the mine by 10–70 m to the roof level of the mined-out area. Water table depression extends up to 6–7 km from the mines. Our calculations based on the basin-wide hydro-geological model of Estonia (Vallner, 2003) demonstrated that the amount of water pumped from oil shale mines exceeded by a factor of five the available resource[1] of the Ordovician groundwater body (GWB) in 2007. The quality of the Ordovician GWB does not meet the standards of drinking water (EEIC, 2004; KKM, 2006).

Therefore, the drinking water has been abstracted from the underlying Cambrian-Vendian Voronka GWB and Gdov GWB in the oil shale basin. At that, abstraction has been from two- to three-fold greater than the available resource of these GWBs over the last 60 years (KKM, 2001). The result of this increased pumping is a basin-wide depression of groundwater potentiometric surface which had induced saline water intrusion into deep GWBs (Fig. 3). In addition, the Gdov GWB contains radioactive substances (mainly, isotopes of radium: ^{226}Ra and ^{228}Ra), meaning a person drinking this water receives an annual effective radioactive dose ranging from 0.16 to 0.33 mSv, which exceeds the recommended limit by up to 3.3 times (KKM, 2006). Because of oil shale mining, the state of GWBs in the mining area of Estonia is characterised as bad according to the classification of the WFD (EU Directive, 2000).

Pollution of underground water resources: Exhausted underground mines in Estonia are flooded. These abandoned mine caves comprise a total area of 220 km^2 (Fig. 2), with 170×10^6 m^3 of water contained within them. The sulphate content of this water increased sharply from 300–600 mg/l to 1200–1500 mg/l in the two years following flooding as a result of the oxidation products of pyrite leaching from carbonate rocks. The sulphate content has later decreased, but still remains higher than the natural background (Erg, 2005).

As a result of the flooding of closed mines, the groundwater table began to rise in the densely populated part of the study area. A number of places with comparatively low topography were drained because of mine dewatering over several decades. These areas suffered from excessive moisture, and some were even flooded after the cessation of mine drainage. Today, the water table is artificially maintained at a suitable elevation in several of the abandoned mines to prevent the disadvantageous side effects of mine flooding. This involves building additional and expensive drainage systems in settlements.

Table 4
Water pollution discharged into rivers due to mine dewatering in 2002, 10^{-6} t/GJ of oil shale produced (calculated based on EP, 2003).

Polluter	Emission value
Biochemical oxygen demand (BOD)	1.66
Total nitrogen (N_{tot})	3.22
Phosphorus (P_{tot})	0.02
Sulphates (SO_4)	847.4
Oil	0.03
1-Basic phenols	0.009[a]
2-Basic phenols	0.004

[a] Emissions of phenols are low compared to other pollutants, therefore high precision in reporting of emission values was applied.

Pollution of surface water resources: Because of mine dewatering, the thickness of the aeration zone has increased from 1–3 m to 20–40 m in bedrock containing pyrite. Because of contact between the air and the pyrite, oxidation takes place and causes increased sulphate concentrations in mine water.

Mine water is pumped out and discharged through pipelines to two natural sedimentation ponds from where water polluted with sulphate flows into rivers. Mine water is also polluted by nitrogen, phosphorous and phenols (Table 4). Because of mine water pumping sulphate concentration is high in most rivers in the region (EEIC, 2009), as well as in nearby lakes, which include also the 40 picturesque lakes of the Kurtna Landscape Reserve (Fig. 2). The content of sulphate in some of the lakes has increased to 160–259 mg/l between 1946 and 2000 (Erg, 2005) in 1937, the sulphate content of these lakes was in the range of 1–7 mg/l (Riikoja, 1940).

3.2.2. Electricity and thermal energy generation

Eesti and Balti PP, both operated by Joint Stock Company (JSC) Narva PPs, a subsidiary of EE Ltd. (hereinafter referred to as "Narva PPs"), are the two largest consumers of oil shale and producers of oil shale-based electricity and heat (Table 5). Kohtla-Järve and Ahtme PP, both operated by JSC Kohtla-Järve PPs, a subsidiary of EE Ltd. (hereinafter referred to as "Kohtla-Järve PPs"), mostly consume oil shale for the purposes of heat generation (Fig. 4).

The construction of the Kohtla-Järve PPs was initiated because of the energy demands of oil shale processing factories. Later, the two plants were connected with overarching electricity and heat networks, and they started to provide energy to nearby cities. The construction of the Narva PPs was launched because of increasing electricity demand in the 1950s–1960s (Kala and Vabar, 1979) (Table 5).

All of the PPs operating on oil shale are steam turbine power-generation plants. The thermal energy of steam produced by the combustion of fuel (e.g., oil shale) is converted into mechanical energy that turns the generators. The remaining heat in outlet steam can be processed to meet requirements in heat by industries or inhabitants of nearby towns (e.g., Kohtla-Järve PPs); or the steam is exhausted into a condenser, it allows to generate electricity more efficiently (e.g., Narva PPs), but almost all the steam energy is lost to the environment by cooling water (e.g., the Narva artificial lake) and only a small quantity could be processed to generate and transmit the heat to remote users.

Pulverised firing (PF) technology was used in all of the oil shale PPs until 2004. One 200-MW power unit at Balti PP and one

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[1] The 'available groundwater resource' is a term of the Water Framework Directive (WFD) (EU Directive, 2000). It expresses the long-term natural average rate of overall recharge of a GWB. If the real abstraction from a GWB exceeds its available resource then an overexploitation of groundwater takes place resulting in an excessive lowering of the pressure in aquifers and deterioration of the groundwater quality. Available groundwater resources of all GWBs of the oil shale basin have been determined by investigations.

Table 5
Installed capacity and net efficiency of oil shale energy use by power plant as of 2002 (Ots, 2004).

Power plant	Placed into operation in...	Installed capacity (MW)		Net efficiency of oil shale energy use (%)[b]	Electricity/heat output ratio, % in GJ terms
		Electricity	Heat[a]		
Kohtla-Järve PP	1949	48	534	70.3	7/93
Ahtme PP	1951	73	338	61.4	10/90
Balti PP	1959–1962	1,624	505	29.4[c]	69/31
Eesti PP	1969–1973	1,610	84	27.2[c]	98/2

[a] Calculated based on heat output to consumers.

[b] Calculated based on EE (2002) and ESO (2009). The quantity of energy self-consumed by the power plants and distribution losses are taken into account.

[c] Efficiency of PP until the renovation of a power unit with a CRF boiler.

200-MW power unit at Eesti PP were repowered and upgraded to 215 MW with two circulating fluidised bed (CFB) boilers in 2005–2006 (Ots, 2004). Both technologies (PF and CFB) are currently used in Narva PPs.

About 10.6 × 10^6 t (88.27 × 10^6 GJ) of commercial oil shale was consumed for electricity and heat generation in the PPs in 2002. Of this figure, 68% and 29% was used by Eesti PP and Balti PP, respectively; Ahtme PP and Kohtla-Järve PP, together, consumed 3% of the oil shale amount (Fig. 4). Electricity is the main product of the Eesti PP; the Kohtla-Järve PP produces mainly thermal energy (i.e., heat) (Table 5). Later on, the pressures on the environment (i.e., the pressure per GJ) of these plants could be considered as a basis to compare the environmental pressure occurring from the operation of other solid fuel-based producers of electricity and heat.

In total, the gross production of electricity was 27.79 × 10^6 GJ, and the production of heat was 5.47 × 10^6 GJ (Fig. 4). The power plants net output was 25.20 × 10^6 GJ of electricity and 5.08 × 10^6 GJ of heat, which was 90% of the total electricity and 16% of the total heat produced in Estonia in 2002. Of the electricity and heat produced from oil shale, 21.24 × 10^6 GJ and 4.39 × 10^6 GJ (i.e., 25.67 × 10^6 GJ total), respectively, was consumed by end users in Estonia (i.e., the distribution losses are accounted) and exported abroad. Based on the final net output of energy (i.e., electricity and heat), the energy-recovery ratio of energy stored in oil shale (i.e., the efficiency of use of the resource energy by the whole "electricity and heat generation" branch) was 29%. This value decreased to 24.1% when accounting for oil shale losses during mining (i.e., 22.6% and 24.4% in Eesti PP and Balti PP, respectively, and 58.7% and 51.3%

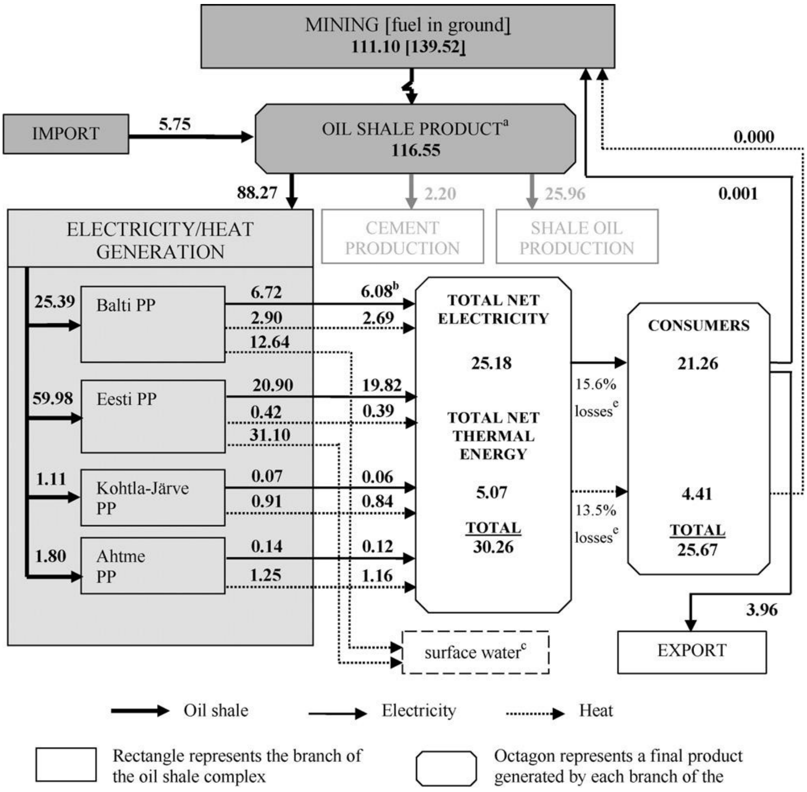

Fig. 4. Energy flow diagram for the oil shale life cycle in electricity and heat generation in the power plants in 2002, 10^6 GJ. [a]Quantity of oil shale stored in stock at the beginning of the year was taken into account. [b]Self-consumption of energy (i.e., electricity and heat) by PPs is taken into account. [c]Data on heat wasted with cooling water are not reported for Kohtla-Järve PP and Ahtme PP, as the PPs recycle cooling water from cooling towers located on-site. [d]Due to the lack of data on oil shale losses in the enrichment process (in tonnage and energy terms) in 2002, the analysis of that stage of the process was omitted from the study of the efficiency of oil shale energy use. [e]Distribution losses.

Table 6
Air pollutant emissions from operation of oil shale based power plants in 2002 (till renovation) and in 2006 (after renovation), 10^{-6} t/GJ of net energy generated (i.e., electricity and heat) (calculated based on EE, 2002).

Polluter	Narva PPs (till renovation)		Narva PPs[a] (after renovation)		Kohtla-Järve PPs	
	Eesti PP	Balti PP	Eesti PP	Balti PP	Kohtla-Järve PP	Ahtme PP
Sulphur dioxide (SO_2)	1,875	2,855	2,012	53.9	1,949	1,989
Nitrogen oxides (NO_x)	359.3	330.1	308.5	94.2	153.3	151.0
Solid particulates (PM_{10}, $PM_{2.5}$)	386.0	1,928	8.5	484.7	103.8	293.2
Carbon monoxide (CO)	–	–			23.4	15.6
Carbon dioxide (CO_2)	333,221	303,125	307,914[b]	289,194	148,658	161,638

[a] Data on quantities of electricity and heat energy produced separately by the Eesti and Balti PPs in 2006 are not reported by EE Ltd. We therefore employed data on quantities of polluters emitted in 2006 (EEIC, 2009) and the information on energy generated in 2006/2007 economic year in the estimates (Narva PPs, 2007).

[b] The data of 2007 (calculated based on Shogenova et al., 2009; Narva PPs, 2007; ESO, 2009).

in Kohtla-Järve PP and Ahtme PP, respectively (Table 5)). Repowering two new boilers with CFB technology increased efficiency of electricity production of the aggregates by 2%. 43.74×10^6 GJ (or 50%) of the total oil shale energy consumed was discharged with cooling water into the Narva artificial lake (Fig. 4).

3.2.2.1. Emissions into air. SO_2, solid particulates and CO_2 are major gaseous emissions from the Eesti PP (where the main product is electricity) and from the Kohtla-Järve PP and Ahtme PP (where the PPs produce mainly thermal energy) per GJ of product generated (Table 6). The renovation of power units in Narva PPs with installation of more efficient flue gas filters in 2005 led to a remarkable reduction of pollutant emissions into the air (e.g., SO_2, NO_x and solid particulates) (Table 6). The emission of pollutants into the air from Kohtla-Järve PPs has not changed since 2002. On the whole, because of implemented environmental protection activities and the decline in electricity demand (ESO, 2003), emissions of SO_2, NO_x and solid particulates from all of the PPs have decreased 2.7, 1.5 and 6.3-fold, respectively, from 1990 to 2006 (EEIC, 2009). This has contributed to decreased SO_2 and NO_x concentrations in the ambient air of the region (Liblik and Kundel, 1995; Liblik and Punning, 1999, 2005), which also decreased the risk of acidification of lakes and forests of Southern Finland and of the Leningrad area (oblast) in Russia. The reduced levels of air pollution by SO_2 and NO_x now meet the requirements of a directive on national emissions from atmospheric pollutants (EU Directive, 2001).

CO_2 emission was reduced 5–10% due to the installation of upgraded boilers at Narva PPs; CO_2 emissions from the repowered PPs were about $289–308 \times 10^{-3}$ t CO_2/GJ after the upgrade, in comparison with $303–333 \times 10^{-3}$ t CO_2/GJ before the upgrade (Table 6). CO_2 emissions from the PPs operating on oil shale contributed 63% and 65% of Estonia's total CO_2 emission from energy sector in 2002 and in 2007, respectively (NIR, 2010). Because of high CO_2 emission values from oil shale PPs, Estonia is one of the leaders in the European Union in CO_2 emission per total primary energy supply (TPES) (Eurostat, 2009).

3.2.2.2. Pressure on water resources. The quantity (4.1×10^6 m^3) of water used by oil shale PPs for technological needs (i.e., condensing water and auxiliary water for boilers and heat networks) was more than five times higher than Estonia's total domestic water use in 2002 (EE, 2002; EEIC, 2009). Water intake at all PPs occurs via surface and underground water bodies. The Ahtme PP and Kohtla-Järve PP consume water mostly for heat networks and for hot water production, and the Balti PP and Eesti PP use water mainly for cooling the steam exhaust (Table 7). At the Narva PPs, the cooling water is withdrawn from and discharged (1.5 GJ of wasted energy per GJ of energy produced) into Narva artificial lake. Kohtla-Järve PPs divert water back to cooling towers located on the plant grounds (Ots, 2004).

The waste water from the heat network and storm water collected on the plant grounds is treated in on-site wastewater treatment facilities and discharged back to the environment at the Eesti, Balti and Ahtme PPs. A wastewater treatment facility has not been built at the Kohtla-Järve PP, and waste is directed to a municipal treatment plant.

In 2002, the Balti PP was the leader in emissions into water for all pollutant components per GJ energy generated (Table 7) because of (occasional) discharges of water from the ash fields. These discharges occur if heavy rainfalls bring excess water to the ash fields, which add to the water used to remove ash from the plant (see Section 3.2.2.3). In the years (e.g., 2001 in Table 7) when discharge of water does not occur (in dry years, years with low level of precipitation), pollution emissions per GJ energy generated are noticeably lower.

Table 7
Water use and water pollutant emissions from operation of oil shale based power plants in 2002 (the data of Balti PP is presented also for 2001), m^3 and 10^{-6} t/GJ of net energy generated (i.e., electricity and heat) (calculated based on EE, 2002, 2003).

	Narva PPs			Kohla-Järve PPs	
	Eesti PP	Balti PP (2002)	Balti PP (2001)	Kohla-Järve PP	Ahtme PP
Water use [m^3/GJ]					
For heating purposes	0.001[a]	0.002	0.002	0.3	0.4
As condensing water	36.9	42.6	45.9	0.2	0.2
For heat networks	0.04	0.16	0.11	0.18	0.15
Emissions into water [10^{-6} t]					
Wastewater [m^3/GJ]	0.09	0.25	0.24	–	0.14
Ash field water discharge (diluted) [m^3/GJ]	–	0.08	–	–	–
Waste heat with cooling water [GJ/GJ]	1.61	1.44	1.56	–	–
Total suspended solids (TTS)	0.72	2.62	0.07	–	0.44
Total nitrogen (N_{tot})	0.07	0.46	0.02	–	0.06
Phosphorus (P_{tot})	0.01	0.04	0.001	–	0.04
Sulphates (SO_4)	0.86	84.1	7.01	–	48.1

[a] Quantities of water use for heating purpose are low compared to other categories of water use, therefore high precision in reporting was applied.

Table 8
Main specific parameters of oil shale retorting processes in the Kiviter and Galoter technologies.

	Unit	Kiviter technology	Galoter technology	Reference
Oil shale	GJ/t of oil shale	11.4	8.5	EP (2003)
Oil shale lump size	mm	25–125	Under 25	Soone et al. (2006)
Oil shale use per t of shale oil produced	t/t	8.0	8.8	
Shale oil	GJ/t of shale oil	39.40	39.77	Yefimov (2000)
Retorting gas	1000 m^3/t of shale oil [10^{-3} GJ/m^3]	3.4–3.8 [3.7–3.4]	0.4 [49.9–54.0]	Yefimov (2000)
Solid waste	t/t of shale oil [GJ/t]	3.8 [4.1]	4 [n.d.]	

n.d., data not available.

3.2.2.3. Pressure on land resources and solid waste generation. About 3.1 km^2 of land was destroyed because of oil shale mining for electricity and heat generation in 2002. A value of energy (i.e., electricity and heat) that could be produced from 1 m^2 of oil shale deposit field, if the efficiency of oil shale extraction and energy generation are taken into account depends on PPs: namely, it was 6.4 GJ and 6.9 GJ/m^2 in Eesti PP and Balti PP, respectively, and 14.4 GJ and 16.5 GJ/m^2 in Ahtme PP and Kohtla-Järve PP, respectively.

One major type of solid waste, ash, was generated at the oil shale PPs. This ash is characterised as a hazardous waste (EU Directive, 1999) because of the method of waste disposal, which involves transporting ash to dumps using a hydraulic ash removal system (HRS). About 163×10^{-3} t of ash per GJ was generated in the Narva PPs (i.e., 162×10^{-3} t and 152×10^{-3} t in the Eesti PP and Balti PP, accordingly), and 71.1×10^{-3} t was generated at the Kohtla-Järve PPs (i.e., 65.1×10^{-3} t and 72.3×10^{-3} t in the Kohtla-Järve PP and in the Ahtme PP, respectively) in 2002. The quantity of ash generated at the PPs contributed over 83% (5.3×10^6 t) of the total amount of hazardous waste generated in Estonia in 2002 (KKM, 2003), and over 95% (5.1×10^6 t) of the total amount of ash generated was disposed in ash fields. The overall amount of oil shale ash disposed in ash fields is 258×10^6 t in a 20 km^2 area (KKM, 2005). The disposal of hazardous oil shale ash leads to contamination of soil and groundwater. The pH of the highly toxic ash leachate is about 12.4–12.7. Groundwater is also polluted with oil products, phenols, toluene and xylene (Sørlie et al., 2004). According to the data of the database of past pollution sites, the area of groundwater polluted by oil shale ash leachate was 9 km^2 (Salu and Metsur, 2004).

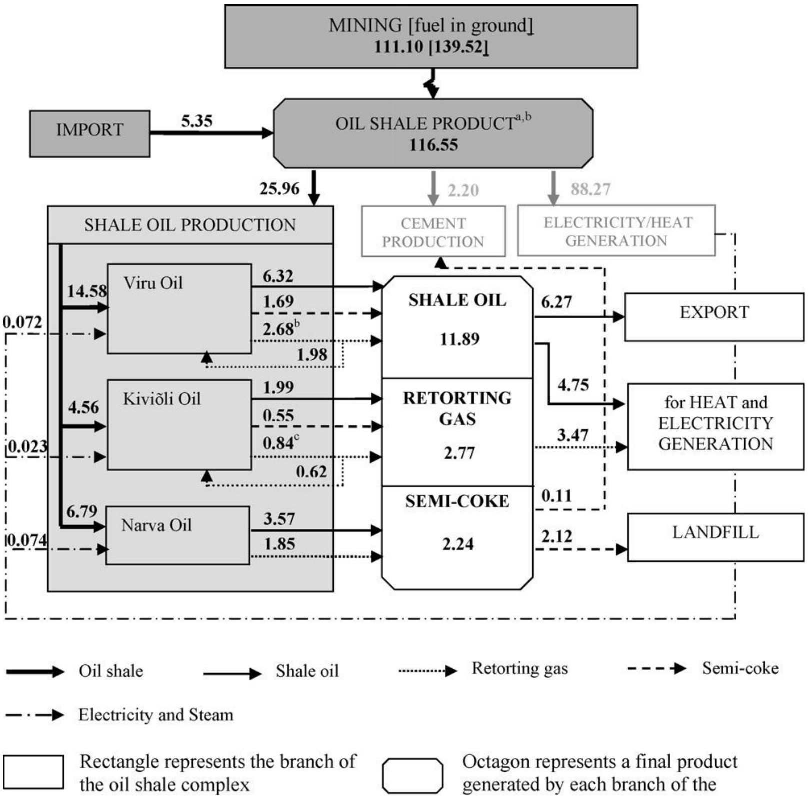

Fig. 5. Energy flow diagram for the oil shale life cycle in shale oil production in oil factories in 2002, 10^6 GJ. [a]Because of the lack of data on oil shale losses in the enrichment process (in tonnage and energy terms) in 2002, the analysis of that stage of the process was omitted from the study of the efficiency of oil shale energy use. [b]Quantity of oil shale stored in stock at the beginning of year was added. [c]Values of retorting gas generated and reused and electricity consumed were estimated based on Yefimov (2000) and Rudin and Serebryannikov (1988).

3.2.3. *Shale oil production*

Shale oil is produced by pyrolysis (i.e., retorting) of oil shale. Oil shale is heated to the temperature at which organic part of the oil shale is decomposed in the absence of oxygen into shale oil, gas (retorting gas) and residues—semi-coke, ash, pitch residue (i.e., fusses) and phenolic water. Two types of retorting technologies are used in Estonia: vertical gas generator technology, where gas is used to transfer heat (Kiviter technology, in use at the Viru oil factory (Viru Oil) and Kiviõli oil factory (Kiviõli Oil)), and solid-heat-carrier technology, in which circulated solids are used as heat carrier (Galoter technology, in operation at Narva Oil factory (Narva Oil)) (Yefimov, 2000). Oil shale with different lump sizes and energy values is used in the Kiviter and Galoter technologies (Table 8).

The processing of oil shale requires external energy in the form of electricity, (retort) gas, and steam. The consumption of recycled retorting gas is 138–153 × 10^{-3} GJ/GJ of oil shale consumed at Kiviter technology, 5.4–5.1 × 10^{-3} GJ and 8.5–10.6 × 10^{-3} GJ of electricity, and 9.1–11.4 × 10^{-3} GJ and 2.4–3.7 × 10^{-3} GJ of heat and steam per GJ of oil shale consumed in the Kiviter and Galoter technologies, respectively (calculated based on Yefimov, 2000). Additionally, external energy flows (e.g., electricity, heat) are used to process shale oil and phenols into clean generator gas, etc., i.e., to produce marketable products. However, the external energy flows were omitted from the study because of a lack of publicly available data.

About 11.89 × 10^6 GJ (0.28 × 10^6 t) of shale oil and 3.24 × 10^6 GJ of retorting gas (including natural gas gasoline) was produced from more than 25.96 × 10^6 GJ (2.3 × 10^6 t) of oil shale consumed by the oil factories in 2002 (Fig. 5). Over 2.24 × 10^6 GJ was released in semi-coke waste (including fusses), where substantial amount of energy containing in semi-coke was also ‘stored’ in landfills (refer Section 3.2.3.3).

More than 50% of shale oil produced was exported and the rest was consumed mainly for heat and electricity generation in Estonia, namely: more than 95% (4.8 × 10^6 GJ) of shale oil produced was used to heat generation and the rest for electricity generation (ESO, 2003).

The energy-recovery ratio of producing shale oil using the Kiviter and Galoter technologies was 64% and 79% (including energy stored in semi-coke waste), respectively. Taking into account the losses in the process of oil shale mining as well as secondary energy consumed (i.e., electricity, steam and retorting gas), the efficiency decreased to 55% and 66% for the Kiviter and Galoter technologies, respectively.

The shale oil-based heat and electricity production could make up to 79% if the oil is used in the cogeneration facilities. Therefore, the overall efficiency of oil shale use is 43% and 52% for the Kiviter and Galoter technologies, respectively, if energy losses in the process of oil shale mining and processing are taken into account.

3.2.3.1. Emissions into air. VOCs, SO_2, NO_x and solid particulates are the main air polluters per GJ from the oil shale retorting processes (Table 9). The oil factories are leaders in the emissions of phenols, VOCs and H_2S among enterprises of Ida-Viru County (EEIC, 2009). Because of the operation of shale oil producing factories, the concentration of H_2S, phenols and VOCs in the ambient air of towns where oil factories are located exceeds permissible levels by several times (Liblik and Kundel, 1995; Liblik and Punning, 1999, 2005).

Table 9
Air pollutant emissions from oil shale retorting technologies, 10^{-6} t/GJ of shale oil produced in 2002 (calculated based on Soone et al., 2004).

Polluter	Kiviter technology (Viru Oil, Kiviõli Oil)	Galoter technology (Narva Oil)
Sulphur dioxide (SO_2)	172.0	19.1
Nitrogen oxides (NO_x)	13.4	10.9
Solid particulates (PM_{10}, $PM_{2.5}$)	8.8	66.4
Carbon monoxide (CO)	8.2	n.d.
Hydrogen sulphide (H_2S)	1.3	0.03
Volatile organic compounds (VOCs)	115.0	215.0
Ammonia (NH_3)	n.d.	3.23
Phenols	0.83	0.41

n.d., data not available.

3.2.3.2. Pressure on water resources. Wastewater is generated during oil shale processing because of the moisture of the resource and processing water or steam used in the Kiviter and Galoter retorting processes. About 35.0 m^3 and 4.3 m^3 of wastewater is generated per GJ of shale oil, with phenol concentrations of 3900 mg/l formed in the Kiviter retorting process and 1500 mg/l in the Galoter retorting process (Yefimov, 2000).

The heavily contaminated wastewater produced by the Galoter technology is directed for combustion into the boilers of the Eesti PP. The wastewater generated by the Kiviter process is treated at the factory using oil separation and dephenolation processes (Kamenev et al., 2003). The dephenolated water is combined with industrial and municipal wastewaters and directed to biological treatment facility and discharged into the Gulf of Finland.

3.2.3.3. Pressure on land resources and solid waste generation. About 18.0 and 22.2 GJ of shale oil (for the Kiviter and Galoter technologies, respectively) could be produced from a 1 m^2 oil shale deposit field taking into account the efficiency of oil shale extraction and shale oil generation processes. In 2002, less than 1.0 km^2 of land in the Ida-Viru County was transformed to mined-out land due to oil shale mining for shale oil production.

Semi-coke (i.e., solid residues), fusses (i.e., oil residues with high-ash fractions of oil shale, which contain polycyclic aromatic hydrocarbons (PAHs), phenols and other hazardous substances (Kattai, 2003; VKG, 2009)) and ash (called black ash) generated in the process of shale oil production are classified as hazardous wastes (EU Directive, 1999).

The waste outcome (i.e., black ash) from the operation of the Galoter technology was 101 × 10^{-3} t/GJ of shale oil, or more than 0.33 × 10^6 t in 2002 (KKM, 2003), and this volume was transported for disposal into the ash fields of Narva PPs (Pikk, 2004).

About 97.2 × 10^{-3} t of semi-coke and 2.3 × 10^{-3} t of fusses are generated per GJ energy of shale oil produced using Kiviter technology. The amount of waste generated comprised over 0.8 × 10^6 t of semi-coke and 0.02 × 10^6 t of fusses, where 96% of the semi-coke volume and 100% of fusses were stored in landfills, and the rest of the wastes were burned in boilers in the process of cement production in 2002. The quantity of fusses burned has increased during recent years, and since 2007 all the fusses generated are recycled.

To date, about 96 × 10^6 t of semi-coke is stored in an area of 2.5 km^2 located close to the oil factories. Semi-coke contains a wide range of environmentally hazardous compounds, including PAHs and water soluble salts. The organic part of semi-coke, which comprises 9–16%, can cause self-ignition of semi-coke (Otsa et al., 2003). A large amount of leachate is formed in the process of precipitation infiltration. The pH of the leachate varies from 8.47 to 12.54. The polluted area of the groundwater is 2.5 km^2, and the pollution reaches a depth of 40–52 m (Otsa et al., 2003).

Initially, fusses were buried together with semi-coke. However, in 1970, factories started to dispose the fuss waste separately. To date, the total area of fuss lakes is 0.02 km^2 with a depth of 7–10 m, where about 0.14 × 10^6 t of fuss is stored (Kattai, 2003). The fuss lakes also contaminate surrounding soils and groundwater (Kattai, 2003; Sørlie et al., 2004). Recently, a project for covering and hydrodynamically isolating the semi-coke waste disposal mounds has been launched.

4. Discussion and conclusions

Over decades, oil shale was the only resource for electricity generation in Estonia. The recently established official policy for the electricity sector of Estonia until 2020 has been drawn based on the continuation of considerable use of oil shale (MKM, 2009), and additional blocks at the Narva and Viru oil factories are under development (VKG, 2009). This means that increase of the production and consumption of oil shale could be well expected in the future, and the burden of the oil shale complex will continue to dominate environmental concerns associated with rational use of land and water resources, climate change and energy efficiency in Estonia.

This study employed the general principles of LCI and MFA approaches to examine the environmental pressure throughout the oil shale life cycle, namely, mining and consumption for electricity and heat generation, and for shale oil production. The analysis was focused on a final product (i.e., oil shale, electricity, heat and shale oil), but not on functions delivered by use of the products. The quantified reference flows allowed us to assess the environmental pressure caused by the production of the GJ of product(s), the environmental pressure associated with the process of operation of the facilities during one year, and the pressure on the environment, accumulated since the oil shale resource production and consumption began. This was done to find the most polluting branch/facility of the complex and to understand the most relevant aspects of oil shale determining the peculiarities of “use of resource-pressure to the environment”. The results of the analysis performed can be used by policy-makers as a basis for further decisions on the development of the oil shale complex. The energy-recovery ratio investigated for each branch/facility allowed us to compare the efficiency of oil shale consumption in them. The results of the inventory could also be considered to be used as a starting point for further research on the environmental problems associated with oil shale production and consumption in Estonia.

The results of the study showed that oil shale mining has a major pressure on land and water resources in the region. On average, less than 80% of the oil shale is extracted from oil shale resource reserves exploited. To date, the total mined-out area comprises about 13% of the total territory of Ida-Viru County. Of the total mined-out area, 27% is subsided land and 46% is unstable. Water resources in the region are under pressure in two ways, as follows: (a) overexploitation of underground water resources (on average, 1.6 m^3 of water per GJ of oil shale is withdrawn from a mine) because of the localisation of oil shale beds in hydrologically sensitive environments (i.e., deeper than the uppermost water body, the Ordovician GWB; Fig. 3); and (b) pollution of surface and underground water bodies. As a result of the operations of oil shale complex, the uppermost aquifer (i.e., the Ordovician GWB), the provider of the regional drinking water supply, has become polluted over an area of 1200 km^2, leading to the overexploitation of deeper aquifers over the last 60 years. In turn, this has caused a basin-wide depression of the groundwater potentiometric surface, inducing a risk of saline seawater intrusion into deep GWBs. Because of the uninterrupted water cycle in mines (whereby polluted mine water is discharged into surface water bodies, although some floods occur in abandoned mines), surface and ground water have become contaminated with sulphate and other contaminants. To date, the concentration of sulphates in most rivers and lakes of the region (e.g., the Kurtna lakes) is significantly higher than in the pre-mining period. The polluted water forms a 220 km^2 (170 × 10^6 m^3) “underground sea” in the exhausted mines.

About 74% (or 10.4 × 10^6 t) of oil shale resource energy extracted and used in the oil shale-based electricity and heat branch (the data from 2002) is characterised by an average efficiency of 29% (or 24% if all relevant energy flows are considered). Among the consumers (i.e., the PPs) of the branch, the Eesti PP recovers oil shale energy with the lowest efficiency (i.e., 22.6%); it is a major oil shale-consumer and main electricity-producer in Estonia producing 69% of the total net electricity used in Estonia. About 50% of the resource consumed in the PPs is transformed into hazardous solid wastes disposed close to the PPs (i.e., to date, 20.1 km^2 or 0.6% of the territory of Ida-Viru County is occupied by ash disposal fields), contaminated by leachate generated polluting underground water on the territory of 9 km^2. The oil shale consumption (i.e., the generation of electricity and heat from oil shale) makes Estonia a leader in CO_2 emission per capita and TPES among European countries (Eurostat, 2009). High CO_2 emissions from oil shale-based electricity production have become a serious barrier to the implementation of the EU climate change package (EC, 2008) and to participating in the EU emissions trading system (EC, 2007). After the EC reduced the CO_2 quota, Estonia changed from a gross “hot air” seller to a buyer of CO_2 emissions.

More than 22% (or 2.3 × 10^6 t) of the primary energy of oil shale resource extracted is used (in 2002) with an average efficiency of 58% for shale oil production (i.e., 55% and 66% for the Kiviter and Galoter technologies, respectively). About half of the resource used (i.e., 1.2 × 10^6 t) was converted to hazardous wastes and disposed into landfills, with a total area of 2.5 km^2 which led to the contamination of underground water with hazardous substances. The emissions of dangerous pollutants (e.g., H_2S, phenols and VOCs) contaminate ambient air in towns closest to the oil factories to a degree much higher than permissible levels. This poses a significant health threat to the inhabitants of these towns. The environment and the health of inhabitants are both under considerable negative pressure as a result of operation of oil factories in Estonia, which export abroad about 50–60% of shale oil and pursue economic benefits at the expense of environmental reclamation. 40–50% of oil left in Estonia is used mostly for heat generation with energy conversion efficiency of 79%, which means of 43% and 52% overall efficiency for the Kiviter and Galoter technologies, respectively, if the efficiency of oil shale mining and processing is also taken into account. The overall efficiency of shale oil-based heat production is comparable with the efficiency of oil shale use for heat generation in Kohtla-Järve PP. The main attractiveness of production of shale oil for the producers is that oil shale retorting and shale oil-based heat production is not associated with considerable CO_2 emissions and therefore the production process results less pressure on the climate.

The results of the inventory carried out to examine the environmental pressure throughout the oil shale life cycle reveal four major characteristics of oil shale as a natural resource. The characteristics that determine the quantitative aspects of the “use of resource-impact to the environment” throughout the oil shale life cycle as follows: (1) the low thickness of oil shale beds, leading to the high expansion rate of mined areas; (2) the low energy rating and high specific emissions of greenhouse gases associated with combusting of oil shale; (3) the high content of mineral matter, which generates solid and hazardous wastes further aggravating the high pressure on land; and (4) the deposition of oil shale beds in hydrologically sensitive environments, which leads to the very large scale overexploitation and pollution of surface and ground water in the region.

Despite our detailed analysis of the oil shale life cycle, a number of questions (or challenges) should be considered, many of which could be subjects for further research. These include comparing the environmental pressure that occur from the production of the products (i.e., oil shale, oil shale-based electricity and heat and shale oil) with the pressure associated with the mining of other solid fuels (e.g., coal), with production of other heavy fuels (e.g., oil), and with generation of electricity and heat from other fuels (e.g., coal, gas, shale oil, renewables). Undoubtedly, a final decision on the implementation of alternative fuels in the electricity and heat generation branch in Estonia, or importing fuels from abroad requires a detailed and accurate economic analysis, and this analysis should be a built-in aspect of the political decision-making processes.

Another question/challenge for further research is to estimate "the integrated environmental pressure" associated with the "electricity and heat generation" branch (i.e., with embedded pollution emissions, quantities of solid waste generated and disposed, areas of land occupied, etc. resulting from the oil shale extracted for the consumption in this branch), and that of the "shale oil production" branch as well as "shale oil-based heat and electricity" branch. The latest should embed also comprehensive evaluation of the pressure on the environment associated with "shale oil production" branch. Development of methods for the evaluation of the cumulative pressure on the environment related to the unit of products (electricity, heat, shale oil), as defined in this study should be considered similarly challenging.

The results of the study, as well as the challenges noted, which could be addressed in the future, should be also an integral part of global decision-making process regarding the future development of the oil shale complexes under various market climate rules and water protection, and waste reduction policies in different countries.

Acknowledgements

The authors are indebted to the Ministry of Education and Science of Estonia for grant SF0142497s03 and to the Estonian Science Foundation for grant 6118.

We thank three anonymous reviewers for their constructive comments.

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PUBLICATION III

O. Gavrilova, R. Vilu. Production-based and consumption-based national greenhouse gas emission inventories: an implication for Estonia. *Ecological Economics* 2012, 75, 161–173.

Ecological Economics 75 (2012) 161–173

Contents lists available at SciVerse ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Production-based and consumption-based national greenhouse gas inventories: An implication for Estonia

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ARTICLE INFO

Article history:
Received 30 June 2011
Received in revised form 13 January 2012
Accepted 17 January 2012
Available online 8 February 2012

Keywords:
Estonia
Greenhouse gas inventory
Input–output analysis
Energy
Industrial processes
Agriculture

ABSTRACT

Two national greenhouse gas (GHG) inventories were prepared for Estonia: (1) an inventory that includes GHG emissions from the production of goods and services (i.e., commodities) within its national territory and (2) an inventory of GHG emissions occurring within and outside its national boundaries due to Estonia's consumption of commodities, whether produced domestically or traded bilaterally. The inventories included estimates of energy-related and non-energy-related carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions (converted to CO_2-equivalent, CO_2eq) associated with the production and consumption of commodities, grouped in three main sectors: energy, industrial processes and agriculture. Input–output (IO) analysis, emissions embodied in bilateral trade (EEBT) approaches and the basic methods of the 2006 IPCC Guidelines were used to perform the estimates. The results of the study illustrated that the total CO_2eq emissions associated with consumption in Estonia in 2005 were 18% higher than those associated with production, primarily due to the net import of CO_2eq emissions from countries outside of the European Union.

1. Introduction

Two types of national greenhouse gas (GHG) inventories have been developed intensively during recent years. The first type of national GHG inventory, referred to as production-based (Peters, 2008), was established under the United Nations Framework Convention on Climate Change (UNFCCC (1992)) to (1) analyse the magnitude of each country's influence on climate as a result of its annual GHG emissions (i.e., direct GHGs, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), the halocarbons (HFCs), the perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), and ozone precursors,[1] including carbon monoxide (CO), oxides of nitrogen (NO_x), non-methane volatile organic compounds (NMVOCs) and sulphur dioxide (SO_2)); (2) develop GHG emission-reduction targets (i.e., under the Kyoto Protocol (UN, 1998) and the Copenhagen Accord (UNFCCC, 2010a)); and (3) monitor progress towards achieving the targets that have been set up to mitigate human influence on the climate system. This type of inventory focuses and defines GHG emissions and removals occurring within the territory of a country due to production activities, which are aggregated into the following six sectors: energy, solvents and other product uses, industrial processes, agriculture, land use and land use change (LULUCF) and waste (IPCC, 1997).

The second type of national GHG inventory, which is consumption-based (Peters, 2008), has its roots in the academic community and is becoming an increasingly important alternative accounting method for GHG emissions in the context of globalisation. Globalisation ‘breaks down’ the national boundaries of countries by integrating their economies and societies through the liberalisation of trade and the emergence of a worldwide production market. The latter promotes access to a wide range of goods and services for consumers in different parts of the world due to exports and imports between countries (i.e., international trade). International trade, in its turn, obliterates ‘GHG emission boundaries’. In other words, GHG emissions caused by the production of commodities for export in one country (i.e., country–producer) are accounted for as GHG emissions associated with a country–producer, and this country should attempt to reduce the emissions. However, the exported commodities are consumed in another country (i.e., country–consumer) that does not account for the GHG emissions associated with their production and uses the commodities without any ‘responsibility for climate change’. Therefore, considering GHG emissions associated only with production of commodities and omitting GHG emissions embodied in traded commodities leads to an incomplete understanding of the overall GHG emissions associated with each country on the global scale.

The consumption-based inventory explicitly includes GHG emissions embodied in imported commodities and excludes GHG emissions associated with exported commodities. The results obtained by estimating GHG emissions using a consumption-based inventory

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[1] Because these gases are not GHGs, they are not included in global warming potential; however, they contribute indirectly to the greenhouse effect. Emissions of ozone precursors were included among the items to be reported under the national GHG inventory (IPCC, 2006). However, they were not included in the Kyoto Protocol targets for reducing GHG emissions. For convenience, all gases discussed are referred to as ‘GHGs’.

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doi:10.1016/j.ecolecon.2012.01.020

reflect a more full and adjusted picture of the overall GHG emissions in relation to the actual living standards (i.e., consumption level) of a country.

To date, numerous global-scale and individual case studies analysed GHG emissions estimated by production-based and consumption-based inventories. A brief overview of such studies was summarised in Wiedmann, 2009; Wiedmann et al., 2007; a short list of the latest studies includes Chen and Chen, 2011; Davis and Caldeira, 2010; Edens et al., 2011; Lin and Sun, 2010; Muñoz and Steininger, 2010; Peters et al., 2011a,b; Rodrigues et al., 2010; Su and Ang, 2010; Su et al., 2010. On the whole, GHG emissions associated with production and consumption of commodities were evaluated and recorded for more than 110 countries. The results obtained in the framework of the global-scale studies make possible the quantification of economic and 'GHG emissions' linkages between countries and the identification of the main importer-countries and exporter-countries of GHG emissions embodied in international trade. The individual case studies evaluated for several countries, primarily the members of the Organisation for Economic Co-operation and Development (OECD) (including the 15 old member states[2] of the European Union (EU27)), provide a basis for detailed analysis of the differences between GHG emissions that occur due to production and those that are associated with the consumption of commodities at the sectoral or the product level in these countries and provide a broader understanding of the factors (e.g., trade structure, volume, trade partners) that result in differences in the levels of the emissions. Hence, the global-scale and individual case studies reinforce and benefit each other and can be considered to provide a solid basis for the development of further climate policy.

Estonia is one of the less studied countries. The GHG emissions associated with the production and consumption of commodities in Estonia were recorded only in the framework of global-scale studies (Bang et al., 2008; Davis and Caldeira, 2010; Peters et al., 2011a,b; Rodrigues et al., 2010). No detailed estimated data on GHG emissions embodied in commodities imported and exported and no analysis of differences in GHG emissions on sector level between the production-based and consumption-based inventories were performed. However, Estonia, as a full member of the EU, ratified the Kyoto Protocol; the EU is taking the lead in establishing global agreement to minimise adverse effects of countries' activities on the climate and to implement domestic actions to achieve reductions in GHG emissions by each member country (EC, 2009). It is reasonable to assume that further rational climate policy should be developed based on sound knowledge and understanding of the objective situation.

In the present study, we compiled national production-based and consumption-based inventories of three main gas emissions, CO_2, CH_4 and N_2O for three main inventory sectors (energy, industrial processes and agriculture) of Estonia for 2005. For CH_4 and N_2O, emissions were converted to CO_2-equivalent (CO_2eq) emissions using the corresponding global warming potential of the 100-year time horizon provided by (IPCC, 1995) and established to be used under the Kyoto Protocol (UN, 1998). Specifically, we investigated energy-related CO_2eq emissions caused by the combustion of energy sources (i.e., the energy sector) associated with the production, bilateral trade and consumption of commodities as well as those that occurred in the process of primary fuel extraction (i.e., fugitive emissions; energy sector) and those associated with the production and consumption of the primary fuels. In addition, we examined non-energy-related CO_2eq emissions resulting from manufacturing processes and agricultural activities (i.e., industrial processes and the agriculture sector of national inventories) in the production of goods consumed in Estonia or exported abroad and emissions associated with the importation of these goods.

The main principles of input–output (IO) analysis (Eurostat, 2008), the basic methods reported in the 2006 IPCC Guidelines (IPCC, 2006) and the main rules of the emissions embodied in bilateral trade (EEBT) approach (Peters, 2008) were employed in completing the inventories. The potential uncertainties and challenges associated with completing a detailed and accurate consumption-based GHG inventory of Estonia are also discussed in the present study.

2. Methodology and data

The fundamental methodological difference in estimating CO_2eq emissions using production-based and consumption-based inventories is that the latter also accounts for CO_2eq emissions embodied in commodities imported and exported between countries (Ahmad and Wyckoff, 2003), as shown in the following:

$$E_{DCd} = E_{DPd} - E_{EXdj} + E_{IMjd}, \tag{1}$$

where E_{DPd} represents the total CO_2eq emissions associated with the production of commodities within the boundaries of country *d*, E_{DCd} represents the total CO_2eq emissions associated with the consumption of commodities in country *d*, E_{EXdj} is the total CO_2eq emissions embodied in the commodities produced in country *d* and exported to countries 1…*j* and E_{IMjd} represents the total CO_2eq emissions embodied in the commodities produced in countries 1…*j* and imported to country *d*.

The total CO_2eq emissions associated with the production and consumption of commodities in Estonia in 2005 were determined as the sum of energy-related (i.e., due to energy source combustion and primary energy extraction) and non-energy-related (i.e., resulting from manufacturing and agricultural activities) CO_2, CH_4 and N_2O emissions (converted to CO_2eq emissions (IPCC, 1995)).

The standard monetary IO tables developed by the OECD (OECD, 2010) and the Statistical Office of European Communities (Eurostat, 2010a) and data on primary and secondary energy fuels combusted (Eurostat, 2010c; IEA, 2003a,b, 2005a,b) were used in the context of the EEBT approach to estimate the energy-related CO_2eq emissions embodied in each of 42 commodities produced in Estonia and in the countries-trade-partners of Estonia. The latter, together with data on the bilateral trade of Estonia (measured in monetary terms; Eurostat, 2010b,d), were used to estimate the energy-related CO_2eq emissions embodied in the import and export of Estonia. The EEBT approach was employed because, first of all, this approach is considered to be the most transparent (Peters and Hertwich, 2008) and more appropriate for the analysis of GHG emissions associated with bilateral trade relationships (Peters et al., 2011a; Su and Ang, 2011), than another calculation approach, multiregional input–output (MRIO). The latter is also widely employed in the framework of consumption-based GHG inventory and reputed to be more complex in use and in more data-demanding. The approaches differ in how they treat imported commodities and, consequently, in the sources of GHG emissions embodied in them. The EEBT does not distinguish between different uses of imported commodities, i.e., whether they are used for final consumption or for intermediate consumption to produce commodities that could be domestically consumed or exported. In other words, the EEBT approach assumes that GHG emissions embodied in commodities imported to a country remain within the boundaries of the country and are not '(re)exported' with commodities in the production process of which imported commodities were used, i.e., the overall GHG emissions 'imported' to a country are considered 'consumed in the country'. Nevertheless, the MRIO approach splits GHG emissions embodied in commodities imported to a country into two parts—for final consumption and for intermediate

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[2] The older member countries are Austria (AT), Belgium (BE), Germany (DE), Denmark (DK), Spain (ES), Finland (FI), France (FR), Greece (GR), Ireland (IE), Italy (IT), Luxembourg (LU), the Netherlands (NL), Portugal (PT), Sweden (SE) and United Kingdom (UK). The new member countries are Bulgaria (BG), Cyprus (CY), the Czech Republic (CZ), Estonia (EE), Hungary (HU), Lithuania (LT), Latvia (LV), Malta (MT), Poland (PL), Romania (RO), Slovenia (SI), and Slovakia (SK).

manufacturing to produce commodities—and accounts for GHG emissions that were '(re)exported' from a country-importer. Therefore, the approach allows the examination of a feedback effect in GHG emissions associated with bilateral trade between a country and its trade-partners (i.e., GHG emissions embodied in imported commodities that were (re)exported back to a country of origin from a destination country (Su and Ang, 2011)). This approach also allows the examination of 'imported' GHG emissions that were (re)exported to other countries in the context of global production and consumption systems (Peters, 2008).

Non-energy-related CO_2eq emissions associated with Estonia's production of several manufacturing and agricultural products (which were disaggregated on a more detailed level as crops, living livestock and meat from livestock, products of the mineral and chemical industries, rather than accepted in the estimation of energy-related CO_2eq emissions) and emissions associated with the bilateral trade of these products were estimated based on the basic methods presented in the 2006 IPCC Guidelines (IPCC, 2006). Data on production and trade, expressed in physical terms (tonnes (t) and heads), and appropriate emission factors were obtained from statistical datasets (ESO, 2010; Eurostat, 2010b; FAOSTAT, 2010), the 2006 IPCC Guidelines (IPCC, 2006) and the national tables of Common Reporting Format submitted to the UNFCCC (UNFCCC, 2010b).

Energy-related CO_2eq emissions (i.e., fugitive emissions) associated with the production of primary energy sources (crude oil, natural gas and solid fuels) in Estonia and Estonia's trade-partners were estimated based on physical data expressed in terajoules (TJ) using the methods of the 2006 IPCC Guidelines (IPCC, 2006); emission factors were obtained from (IPCC, 2006; UNFCCC, 2010b).

Non-energy-related and fugitive CO_2eq emissions associated with product consumption were also estimated by considering the main principle of the EEBT. In essence, the EEBT was considered a superior approach to guarantee consistency in the estimation of energy-related and non-energy-related CO_2eq emissions associated with consumption; since, different datasets (i.e., the input data are measured in monetary and physical terms) and different aggregation/disaggregation of commodities/products were employed in the study.

The detailed methodologies and descriptions of the input data used to estimate energy-related and non-energy-related CO_2eq emissions associated with production, bilateral trade and consumption of Estonia in 2005 are presented in Appendix A.

To simplify the overview of the outcome of the present study, the results regarding energy-related CO_2eq emissions associated with the production and consumption of commodities were grouped and recorded according to 15 main economic sectors (Table B.1 of Appendix B). However, the results on non-energy-related CO_2eq emissions associated with production and consumption of manufacturing and agricultural products were recorded at a more detailed level, i.e., for each category of product.

3. Results

3.1. Energy sector

3.1.1. Emissions due to combustion of primary and secondary fuels related to the production and consumption of commodities

The total output of the Estonian economy was 24,255 million Euros ($24{,}255\times10^6$€) in 2005 (Table 1). Of that output, more than 50% was produced by the commercial sector, 12% by the transport sector and 10% by the engineering and other metal industry sectors. The total export of the Estonian economy consisted of 7434×10^6€ in 2005 (Table 1). Of the total export, engineering and other metal industries and wood and printing industry commodities (30% and 11%, respectively) and services provided by commercial and transport sectors (15% and 16%, respectively) prevailed over goods and services produced by other sectors. The main trade partners for Estonia were Finland, Sweden, Latvia, Germany and Lithuania (Fig. 1). The total import of commodities to Estonia reached 8624×10^6€ in 2005 (Table 1). Of the total import, engineering and other metal industry and chemical industry goods were prevalent. The main importers of commodities to Estonia were Finland, Germany, Sweden, Russia, Latvia and Lithuania (Fig. 1).

The total energy-related CO_2eq emissions ('CO_2eq emissions' in this sub-section) due to the combustion of primary and secondary fuels required to produce the commodities were 15,772 thousand tonnes of CO_2eq ($15{,}772\times10^3$ tCO_2eq) in 2005 (Table 1). The main contributors of CO_2eq emissions to the total CO_2eq emissions were the electricity and thermal energy generation industry (32% of the total emission), the commercial (28%) and transport sectors (12%).

The total CO_2eq emissions embodied in exports were 3703×10^3 tCO_2eq in 2005 (Table 1). Of the total CO_2eq emissions 'exported', those embodied in the transport sector, engineering and in other metal industry, wood and printing industry and chemical industry

Table 1

Production, import and export of commodities by sectors of the Estonian economy in 2005 and associated energy-related emissions. The numbers shown represent 10^6€ and 10^3 tCO_2eq, respectively (Eurostat, 2010a).

Nr	Sector of the economy[a]	10^6€			10^3 tCO_2eq			
		Import	Production	Export	Import	Production	Export	Consumption
1	Fuel extraction industry	83	137	24	263	72	12	322
2	Coke and refined petroleum products industry	462	75	54	769	82	60	792
3	Electrical and thermal energy generation industry	6	676	43	8	5092	307	4794
4	Iron and steel industry	471	247	257	745	104	108	741
5	Non-ferrous metal industry	311	498	206	65	93	39	119
6	Chemical industry	932	566	404	1780	484	397	1867
7	Non-metallic mineral products industry	149	303	97	69	278	89	258
8	Ore extraction industry	18	48	8	25	15	2	38
9	Food, drink and tobacco industry	551	1030	365	240	927	329	838
10	Textile, leather and clothing industry	511	561	549	284	364	356	292
11	Wood and wood products, paper and printing industry	344	1390	796	663	719	439	942
12	Engineering and other metal industry	3369	2453	2211	1131	670	544	1257
13	Agriculture, hunting, forestry and fishing	246	828	145	90	240	42	288
14	Transport	442	2861	1178	406	1935	726	1615
15	Commercial sector	728	12,548	1099	312	4368	253	4427
	Households					328[b]		328
	Total	8624	24,225	7434	6850	15,772	3703	18,919

[a] The data on production, export and import of 42 commodities (in 10^6€ and 10^3 tCO_2eq) were grouped and recorded for the 15 main economic sectors. See also Table B.1 for the classification of the sectors and commodities produced by each sector.

[b] Direct energy-related CO_2eq emissions due to the combustion of primary and secondary fuels by households in Estonia in 2005.

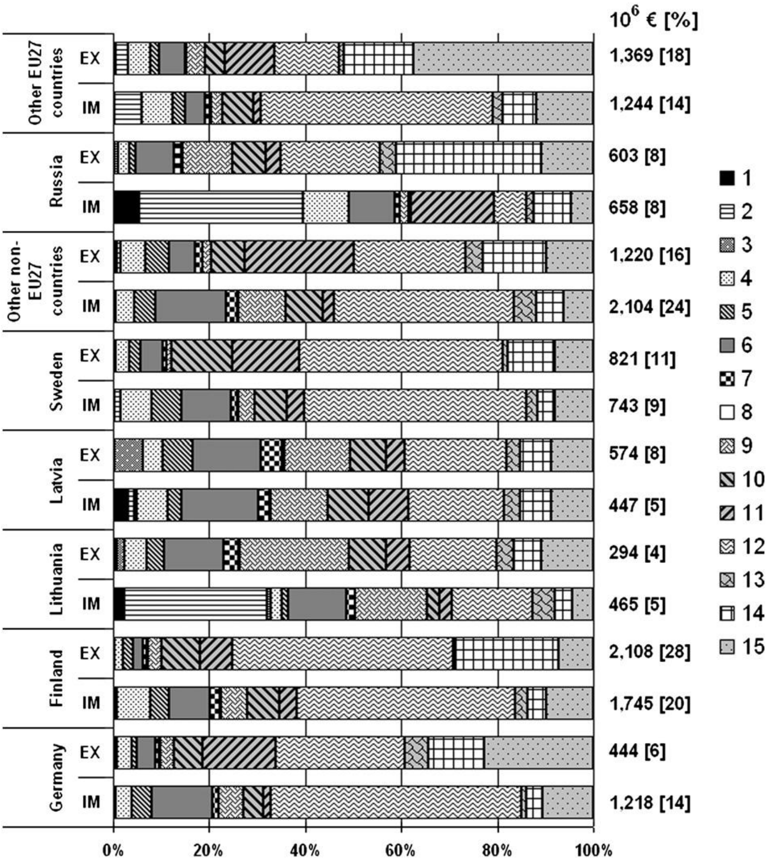

Fig. 1. The import (IM) and export (EX) structures of Estonia in 2005 by economic sector (%) and by Estonia's trade partners [% of the total import and export, respectively]. The numbers shown represent 10^6€ (Eurostat, 2010b,c,d). [a] The data on import and export of 42 commodities were grouped and recorded in accordance with the 15 main economic sectors producing them. (See also Table B.1 for the classification of the sectors and categories of commodities produced by each sector).

commodities were dominant. Finland (21% of the total CO_2eq embodied in the export), Latvia (15%), Sweden (9%) and Russia (10%) were the main destinations for the commodities associated with these CO_2eq emissions (Table 6). In general, Estonia's export of CO_2eq embodied emissions went to countries with total CO_2eq emission intensities lower than that of Estonia, with the exception of Russia and several sectors of Latvia (Tables 2 and 6).

The total CO_2eq emissions embodied in the commodities imported to Estonia were 6850×10^3 tCO_2eq in 2005 (Table 1). Of these emissions, the major contribution was provided by chemical industry goods (26%), engineering and other metal industry products (17%), coke and petroleum products and iron and steel industry commodities (each sector contributed 11% to the total CO_2eq emissions embodied in the import) and goods of the wood and printing industry (10%). Russia, a country with higher values of CO_2eq emission intensities than Estonia (Table 2), exported the most embodied emissions to Estonia (approximately 50%). These CO_2eq emissions were embodied in products of the chemical industry (1310×10^3 tCO_2eq), the wood and printing industry (576×10^3 tCO_2eq) and the coke and refined petroleum industry (510×10^3 tCO_2eq).

The total CO_2eq emissions associated with the consumption of commodities in Estonia were $18{,}919 \times 10^3$ tCO_2eq in 2005 (Table 1). This value is approximately 20% higher than that for CO_2eq emissions associated with production.

3.1.2. Fugitive emissions related to primary fuel production and consumption

The total amount of primary fuel energy produced in Estonia in 2005 was 132,977 TJ (Table 3). The main source of primary fuel energy was oil shale; less than 3% of primary fuel energy was extracted as peat. The total export of primary energy from Estonia made up 261 TJ, or approximately 1%, of the total primary fuels extracted in 2005. Of Estonia's total export, approximately 57% was oil shale; the remainder was peat. Estonia exported oil shale energy to Russia and peat energy to Finland and Sweden. In 2005, the total import of primary energy to Estonia was 36,537 TJ; this energy was imported as natural gas (92% of the total import), coal and oil shale. The main and sole country-exporter of primary fuels was Russia in 2005.

The total energy-related fugitive CO_2eq emissions ('CO_2eq fugitive emissions') occurred in the process of primary energy extraction and amounted to 15×10^3 tCO_2eq (Table 3) in Estonia in 2005. A main source-activity of the total fugitive CO_2eq emission occurred due to the extraction of peat energy. The production of oil shale was not a source for the release of fugitive emissions (UNFCCC, 2010b).

The export of primary energy from Estonia was associated with 0.4×10^3 tCO_2eq of fugitive emissions (Table 3). More than 75×10^3 tCO_2eq of the fugitive emissions were embodied in the primary fuels imported to Estonia in 2005. Of the total CO_2eq emissions, approximately 10% of the emissions were embodied in imported solid fuels (specifically coal; the import of oil shale was not associated with

Table 2
Total energy-related emission intensities of the main economic sectors of Estonia and Estonia's main trade partners in 2005, tCO_2eq/1000€.

Nr	Sector of the economy[a]	Estonia (EE)	Finland (FI)	Germany (DE)	Lithuania (LT)	Latvia (LV)	Sweden (SE)	Russia (RU)[b]
1	Fuel extraction industry	0.52	0.06	0.32	0.11	0.27	0.02	6.55
2	Coke, refined petroleum products industry	1.10	0.31	0.37	1.82	0.08	0.24	2.27
3	Electrical and thermal energy generation industry	7.53	1.22	2.06	0.88	3.36	0.35	12.82
4	Iron and steel industry	0.42	0.67	0.67	0.24	2.02	0.48	4.86
5	Non-ferrous metal industry	0.19	0.09	0.12	0.05	0.16	0.05	1.21[c]
6	Chemical industry	0.86	0.22	0.18	0.17	0.30	0.11	17.42
7	Non-metallic mineral products industry	0.92	0.20	0.29	0.90	1.17	0.23	1.06
8	Ore extraction industry	0.31	0.06	0.11	0.08	0.13	0.12	6.60
9	Food, drink and tobacco industry	0.90	0.23	0.24	0.41	0.41	0.14	2.48
10	Textile, leather and clothing industry	0.65	0.17	0.20	0.20	0.37	0.14	4.41
11	Wood and wood products, paper and printing industry	0.52	0.38	0.15	0.08	0.31	0.14	3.04
12	Engineering and other metal industry	0.27	0.10	0.13	0.16	0.32	0.06	3.85
13	Agriculture, hunting, forestry and fishing	0.29	0.11	0.13	0.13	0.33	0.04	1.96
14	Transport	0.68	0.32	0.46	1.08	1.21	0.31	4.41
15	Commercial sector	0.35	0.13	0.07	0.12	0.16	0.04	3.47

[a] The total energy-related emission intensities of the 15 main sectors were estimated as follows: (1) the energy-related emissions that occur in the process of producing commodities were summed in accordance with the sector classification presented in Table B.1; (2) the monetary output of each commodity was summed based on the same rules; (3) the total energy-related emissions summed for each economic sector were divided by the total output of each sector.

[b] The data for 2000.

[c] The value of the Chinese non-ferrous metal industry was used in the estimates.

Table 3
Production (i.e., extraction), import and export of primary fuel energy in Estonia and associated fugitive (i.e., energy-related) emissions in 2005, in TJ and 10^3 tCO_2eq (ESO, 2010; Eurostat, 2010d).

Primary fuels	TJ			tCO_2eq			
	Import	Production	Export	Import	Production	Export	Consumption
Solid fuels	3056	132,977	261	8	15	0.4	23
Natural gas	33,481	–	–	67	–	–	67
Total[a]	36,537	132,977	267	75	15	0.4	89

[a] The total amount of CO_2eq emissions does not equal the subtotals due to rounding.

the import of the embodied emissions); the remainder of the CO_2eq fugitive emissions were associated with imported natural gas.

The total fugitive CO_2eq emissions associated with the consumption of primary energy in Estonia were $89 \times 10^3 tCO_2eq$ in 2005, approximately six-fold higher than the emissions associated with its production (Table 3).

3.2. Industrial processes

Estonia produced cement, lime, glass and chemical products (i.e., nitric acid and ammonia) in 2005. In tonnage-terms, approximately 45% of the total cement and lime products of Estonia were exported. The export of glass and chemical products made up 17% and 44%, respectively, of the total production. Estonia depended fully on the import of iron and steel products because no iron and steel manufacturing processes exist there. Estonia's import of cement and lime products and chemical products was lower than its export of these products (Table 4).

The total non-energy-related CO_2eq emissions ('CO_2eq emissions' in this sub-section) associated with industrial production were $677 \times 10^3 tCO_2eq$ in 2005 (Table 4). The major share of CO_2eq emissions released was contributed by the production of cement and lime products (59%), and the rest by chemical production.

The total export of manufacturing products by Estonia was associated with emissions of $301 \times 10^3 tCO_2eq$ in 2005. Estonia's CO_2eq emissions were primarily embodied in products exported to Latvia (70% of the total CO_2eq emissions associated with exports), Finland (11%) and Russia (19%) (Table 6). Of the total CO_2eq emissions embodied in exports to Latvia, approximately 40% were associated with cement and lime products and 60% with ammonia. Of the CO_2eq emissions embodied in exports to Finland, 98% were contributed by emissions embodied in cement and lime products. Of Estonia's exports of manufacturing products to Russia, 100% were associated with CO_2eq emissions embodied in cement and lime products.

The total CO_2eq emissions associated with imports to Estonia were $29 \times 10^3 tCO_2eq$ in 2005. The main trade partners in embodied CO_2eq emissions were Finland and Sweden (Table 6). Approximately 41% of the total CO_2eq emissions embodied in imports from Finland were in cement and lime products, and 59% were 'imported' with glass products.

Table 4
Estonia's production, import and export of manufacturing products from industrial processes and non-energy-related emissions associated with them in 2005, in tonnes and 10^3 tCO_2eq (UNFCCC, 2010b).

Product	Tonnes			$10^3 tCO_2eq$			
	Import	Production	Export	Import	Production	Export	Consumption
Cement and lime	28,123	734,427	331,650	14	397	178	232
Glass	61,839	62,056	10,307	14	8	1	21
Nitric acid and ammonia	2532	212,586	94,454	1	272	121	152
Iron and steel	953	–	146[a]	1[a]	—	—[a]	1
Total				29	677	301	406

[a] The re-export of the products. Because it was decided to omit CO_2eq emissions that were associated with imports to Estonia for further re-export, only CO_2eq emissions embodied in the net import (i.e., the quantity of imports minus the quantity of (re)exports) were recorded under the 'Import' column; CO_2eq emissions under 'Export' were reported as'—'.

Approximately 95% of CO_2eq emissions embodied in Swedish imports were in cement and lime products, with the rest in glass products. The total CO_2eq emissions associated with the consumption of cement, lime, glass and chemical products were $406\times10^3\,tCO_2$eq (Table 4), or 40% less than the total CO_2eq emissions associated with their production.

3.3. Agriculture sector

Estonia's trade in living animals consisted mainly of the export of cattle and swine in 2005. Livestock imports (i.e., cattle and pigs, in heads) were approximately 14% and 2% of the total export from Estonia, respectively. Estonia's trade in livestock-meat (in tonnage-terms) was defined by the import and export of beef, pork and poultry. Estonia imported approximately 50% of the total amount of Estonia's production of beef and pork. The import of poultry was more than 112% of the total amount produced in Estonia. The total export of meat from Estonia was approximately 30% of the total import of meat to Estonia. The import and export of cereals were balanced in 2005, i.e., the import of cereals was almost equal to the export of cereals in tonnage-terms. However, Estonia was an absolute net importer of rice and soybeans because it does not cultivate these crops (Table 5).

The total non-energy-related CO_2eq emissions ('CO_2eq emissions' in this sub-section) associated with the production of agricultural products were $814\times10^3\,tCO_2$eq in 2005 (Table 5). The total CO_2eq emissions embodied in Estonian exports of agricultural products were $128\times10^3\,tCO_2$eq in 2005; more than 20% of the embodied emissions were exported with livestock, 34% were exported with pork and 14% with beef, and the emissions associated with the export of cattle-milk contributed approximately 20% of the total emissions associated with exports of agriculture-related products. The destination countries of the CO_2eq emissions embodied in Estonia's exports were Latvia, Lithuania and Poland (Table 6). Of the total CO_2eq emissions embodied in Estonia's exports to Latvia, more than 50% were associated with meat (i.e., beef and pork) and approximately 30% were related to livestock exports. Of the CO_2eq emissions embodied in exports to Lithuania, 85% were embodied in meat and 10% were associated with milk exports. Of Estonia's exports to Poland, more than 85% were associated with livestock exports and more than 10% were associated with meat (Table 5).

The total CO_2eq emissions embodied in imports were $320\times10^3\,tCO_2$eq in 2005; approximately 70% of the total emissions were 'imported' with pork and approximately 20% with beef (Table 5). The majority of CO_2eq emissions embodied in agriculture-related products were imported from Denmark (34% of the total CO_2eq emissions embodied in the imports), Finland (22%) and Germany (12%). Of the CO_2eq emissions embodied in exports from Denmark and Finland, 100% were associated with meat. Germany's agricultural exports to Estonia consisted of approximately 65% emissions embodied in meat and more than 25% emissions associated with soybean imports (Table 6).

In total, $1008\times10^3\,tCO_2$eq were associated with the consumption of agriculture-related products (Table 5). Emissions related to agricultural consumption exceeded those related to agricultural production by 24% in 2005.

3.4. The total CO_2eq emissions associated with the production and consumption of commodities

The total CO_2eq emissions (i.e., energy-related and non-energy-related) associated with the production of commodities in Estonia were $17{,}278\times10^3$ t in 2005; the major share of these emissions occurred in the energy sector. Non-energy-related CO_2eq emissions associated with agricultural products made up 5% of the total, and 4% of the non-energy-related emissions occurred in manufacturing (Fig. 2). The total CO_2eq emissions (i.e., energy-related and non-energy-related) associated with the consumption of commodities were $20{,}420\times10^3$ t. The latter value exceeded the emissions associated with production by 18%. The percentage structure by sector of the CO_2eq emissions associated with consumption was nearly the same as for production-based emissions.

The total CO_2eq emissions embodied in the export of commodities from Estonia were $4132\times10^3\,tCO_2$eq in 2005. The total CO_2eq emissions embodied in the import of commodities during the same period were equal to $7274\times10^3\,tCO_2$eq. Estonia 'net imported' CO_2eq emissions embodied in commodities traded primarily from Russia, China, Kazakhstan, Ukraine and Belarus and 'net exported' to the EU27 countries, the United States, Norway and Switzerland in 2005 (Fig. 3).

Among the EU27 countries, the main 'net importers' of Estonia's CO_2eq emissions were the neighbouring countries of Latvia, Finland, Sweden and Lithuania. The main 'net exporters' of CO_2eq emissions

Table 5

Estonia's production, import and export of agriculture-related products and non-energy-related emissions associated with these products in 2005, in heads, tonnes and $10^3\,tCO_2$eq (ESO, 2010; Eurostat, 2010d; FAOSTAT, 2010).

Agriculture-related product	Unit	Import	Production	Export	Unit	Import	Production	Export	Consumption
Living animals	Heads/year				$10^3\,tCO_2$eq/year				
Cattle		912	249,800	6373		3	626	18	611
Pigs		422	340,100	19,015		0	129	12	117
Poultry		626	2,182,000	27		0	24	0	24
Other livestock[a]		—	46,100	68		—	20	0	20
Meat	t/year				$10^3\,tCO_2$eq/year				
Beef		6636	13,431	1735		60	—[e]	18	42
Pork		19,061	39,521	7805		216	—	44	172
Poultry		15,458	13,778	3034		15	—	3	12
Other meat[b]		102	333	100		2	—	4	−3
Milk[c]		6520	670,427	46,370		5	—	26	−19
Crops	t/year				$10^3\,tCO_2$eq/year				
Cereals		106,394	760,073	130,491		2	14	2	13
Rice		3492	—	399[d]		4	—	—[d]	4
Soybeans		22,085	—	104[d]		13	—	—[d]	13
Total						320	814	128	1008

[a] Living sheep, goats and horses.

[b] Mutton, goat- and horse-meat.

[c] Only fresh cattle-milk was considered; milk-related products (e.g., cream, butter and cheese) were not considered in the framework of the study.

[d] The re-export of rice and soybean crops. Because it was decided to omit energy-related and non-energy-related CO_2eq emissions associated with imports to Estonia for further re-export, only CO_2eq emissions embodied in the 'net import' (i.e., the quantity of imports minus the quantity of (re)exports) were recorded under the 'Import' column. CO_2eq emissions under 'Export' are reported as '—'.

[e] Non-energy-related emissions were included in the emission values reported under 'Living animals' because (ESO, 2010) reports annual data on livestock populations that already include the number of animals slaughtered, new-born, etc.

Table 6
Energy-related and non-energy-related emissions associated with the import and export of commodities to and from Estonia by trade partners in 2005, in $10^3\,tCO_2eq$.

Trade partner of Estonia	Emissions embodied in bilateral trade involving…							
	Goods and services[a]		Primary fuels		Manufacturing products		Agricultural products	
	Import	Export	Import	Export	Import	Export	Import	Export
Belgium (BE)	28	44	–	–	1	–	15	0
Finland (FI)	315	777	–	0.4	16	34	70	8
Germany (DE)	203	199	–	–	1	0	38	8
Denmark (DK)	24	107	–	–	0	0	108	1
Lithuania (LT)	200	206	–	–	0	1	14	27
Latvia (LV)	215	548	–	–	0	209	6	48
Netherlands (NL)	57	64	–	–	0	0	10	2
Poland (PL)	166	36	–	–	2	0	19	18
Sweden (SE)	75	320	–	–	5	0	10	5
United Kingdom (UK)	47	163	–	–	0	0	1	0
Other EU27 countries	180	174	–	–	2	0	25	6
China (CN)	338	10	–	–	0	0	0	–
Russia (RU)	3402	374	75	–	1	56	0	3
United States (US)	43	133	–	–	0	0	0	0
Other non-EU27 countries	1557	548	–	–	2	0	3	1
Total	6850	3703	75	0.4	29	301	320	128

[a] Energy-related CO_2eq emissions embodied in Estonia's bilateral trade of 42 commodities.

were Poland and Germany (Fig. 4). The emission balances of the Netherlands and Belgium, due to bilateral trade with Estonia, were close to zero, because, although these countries were net importers of energy-related CO_2eq emissions, they net exported non-energy-related CO_2eq emissions in agricultural products. In a similar manner, an emission balance with Denmark occurred due to bilateral trade with Estonia; Denmark net imported energy-related CO_2eq emissions from Estonia ($83\times10^3\,tCO_2eq$) but net exported non-energy-related CO_2eq emissions associated with agricultural products ($107\times10^3\,tCO_2eq$) (Table 6).

4. Discussion and conclusions

The present study contributes to current research that investigates the production-based and consumption-based GHG inventories of Estonia and analyses the differences between the emissions associated with these inventories (Bang et al., 2008; Davis and Caldeira, 2010; Peters and Hertwich, 2008; Peters et al., 2011a,b; Rodrigues et al., 2010). The results of the studies completed to date differ, and the differences in the results can be explained by differences in the methods, including the level of sector disaggregation, geographical coverage and the choice of sources of CO_2 emissions for analysis employed in the calculations. Bang et al. (2008) estimated that CO_2 emissions associated with production were higher than emissions associated with consumption in Estonia in 2001. Their study relied on the EEBT approach and considered 57 commodities of 87 countries/regions; CO_2 emissions due to fuel combustion and cement production were analysed. In addition to these two categories of CO_2 emissions, Peters et al. (2011a) also considered CO_2 emissions from gas flaring. In that study, the EEBT approach was employed with 57 commodities of 113 countries; the results showed that CO_2 emissions associated with production were lower than CO_2 emissions associated with consumption in Estonia in 2001. Peters and Hertwich (2008) used the EEBT approach with 57 commodities of 87 countries but focused only on combustion-based CO_2 emissions. Their results showed an excess of consumption-based CO_2 emissions over production-based CO_2 emissions in Estonia in 2001. Davis and Caldeira (2010) and Peters et al. (2011a,b) used the MRIO approach to perform an analysis involving 57 commodities of 113 countries. Davis and Caldeira addressed only CO_2 emissions due to fuel combustion, while Peters et al. additionally considered CO_2 emissions from cement production and gas flaring. The results of both studies showed that CO_2 emissions associated with production were lower than CO_2 emissions associated with consumption of commodities in Estonia in 2004.

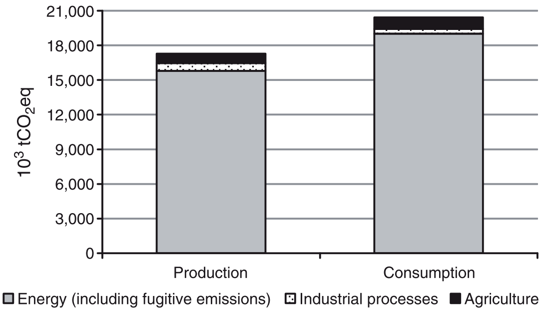

Fig. 2. Energy-related and non-energy-related emissions associated with the production and consumption of commodities in Estonia in 2005, in $10^3\,tCO_2eq$.

In this study, the emissions of three main gases associated with the production and consumption of commodities, CO_2, CH_4 and N_2O, were evaluated in terms of CO_2eq emissions (IPCC, 1995). The study focused on energy-related CO_2eq emissions associated with primary fuel production (i.e., fugitive emissions) and the combustion of primary and secondary fuels and on non-energy-related CO_2eq emissions, i.e., those resulting from manufacturing processes and agricultural activities. The IO analysis, the EEBT approach and the basic methods outlined in the 2006 IPCC Guidelines were employed to estimate the emissions. Data on the production, import and export of commodities, measured in monetary and physical terms, were obtained from different statistical datasets. The results demonstrated that the total CO_2eq emissions (i.e., energy-related and non-energy-related) associated with the consumption of commodities in Estonia were 18% higher than the CO_2eq emissions associated with their production. The energy sector was the main contributor to emissions associated with production and consumption. The major share of CO_2eq emissions embodied in Estonian exports was traded to countries with lower total energy-related CO_2eq emission intensities arising from the production of commodities, mainly to the countries of the EU27, e.g., Finland and Sweden. On the whole, energy-related CO_2eq emissions due to the production of commodities in Estonia play a special role because they are the highest energy-related emission intensities associated with commodities produced by countries of the EU27 (Table 2; Andrew et al., 2009). The CO_2eq emissions embodied in Estonian imports consisted mainly of CO_2eq emissions from Russia and included commodities associated with higher emission intensities.

The differences between the two types of GHG inventories studied in this work lie not only in the values of GHG emissions associated

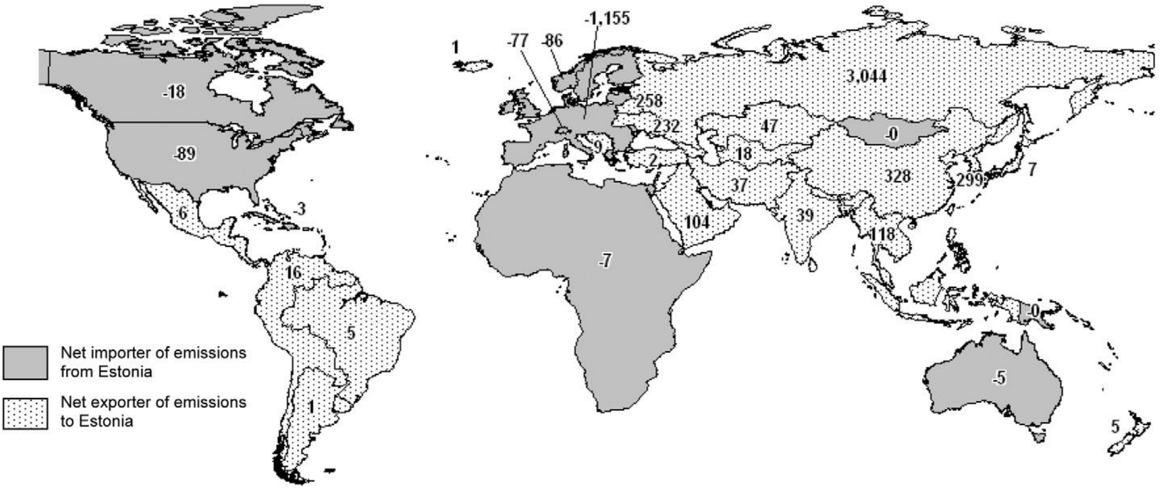

Fig. 3. Energy-related and non-energy-related emissions embodied in the net import of commodities of Estonia by countries and the regions of the world in 2005, in 10^3 tCO$_2$eq. The map was developed based on a map of (Blue Marble Geographics, 2011). Greenland was deleted from the map. The countries and regions (*italics*) were recorded in accordance with the classification presented in FAOSTAT (2010). The values presented in parentheses represent 'CO$_2$eq emissions associated with net import of commodities': (−18) Canada; (−89) United States; (6) Mexico; (−3) *Caribbean* countries; (16) *South American* countries excluding Brazil and Argentina; (5) Brazil; (1) Argentina; (−7) *Africa*; (−77) Switzerland; (−86) Norway; (−1155) *the EU27*; (1) Iceland; (232) Ukraine; (258) Belarus; (9) Albania, Andorra, Bosnia and Herzegovina, Croatia, Serbia, the former Yugoslav Republic of Macedonia; (3044) Russia; (104) *Western Asian* countries excluding Turkey; (1) Turkey; (18) *Central Asian* countries excluding Kazakhstan and Mongolia; (47) Kazakhstan; (−0) Mongolia; (37) *Southern Asian* countries excluding India; (39) India; (299) *Eastern Asian* countries excluding China and Japan; (328) China; (7) Japan; (118) *Southeastern Asian* countries; (−0) Melanesia; (−5) Australia; (5) New Zealand.

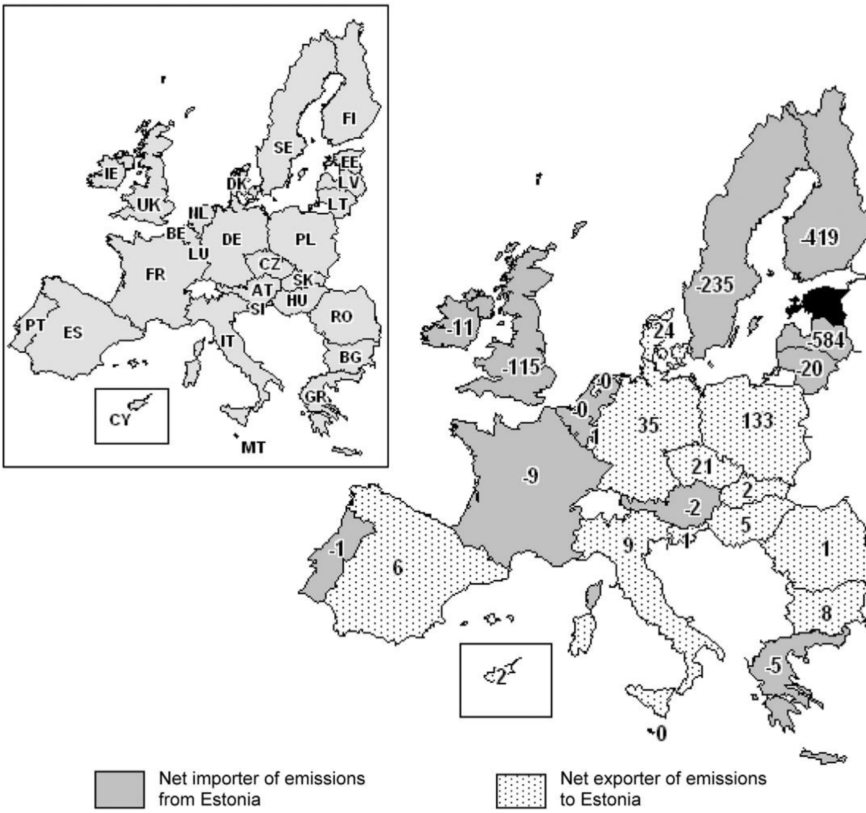

Fig. 4. Energy-related and non-energy-related emissions embodied in the net import of the commodities of Estonia by countries of the EU in 2005, in 10^3 tCO$_2$eq. The map was developed based on a map of (Blue Marble Geographics, 2011).

with production and consumption but also in the evaluation of the total uncertainty values related to each type of inventory. The production-based GHG inventory requires less input data to estimate emissions, which can be obtained from national statistics with country- and technology-specific emission factors. The consumption-based GHG inventory requires more data that depends on international input, and this increases the level of uncertainty in determining the total GHG consumption-based emissions (Peters, 2008; Peters et al., 2011a). Despite the high potential uncertainty, the practice of calculation of uncertainties related to input data and methodological choices is not introduced in the framework of global-scale or country-specific consumption-based GHG inventories. A number of studies have identified, described and discussed uncertainties related to consumption-based inventories (Hertwich and Peters, 2010; Lenzen, 2001; Peters, 2008; Peters et al., 2011a; Wiedmann, 2009). The present study contributes to the discussions provided in those studies and lists major important uncertainties.

First, uncertainties are inherent in the IO tables because the process of development of the IO table assumes a linear relationship between input and output (Lenzen, 2001). Hence, technological, price and structural changes in the economy, which can occur, would have impact the results of the consumption-based inventory. Furthermore, the level of sector disaggregation of the IO tables chosen when performing the consumption-based inventory and harmonising its results with the energy data on primary and secondary fuels combusted brings additional uncertainties related to the GHG emissions associated with consumption. Su et al. (2010) have demonstrated that the difference in CO_2 emissions embodied in exports, which affects the total consumption-based emissions, is approximately 12% in the case of 10 major sector aggregations and 40 sector (i.e., commodities) disaggregations applied in the IO tables. The data on energy combusted itself involves a number of uncertainties; these are mainly associated with missing and incorrectly allocated data and unrealistic outliers in time-series variations (Fujimori and Matsuoka, 2011). In the latter study, the authors argued that the error in the data on energy consumption could reach 35–45% for some countries.

The choice of calculation approach between the EEBT and the MRIO primarily determines the differences in the total GHG emissions associated with consumption because of the different ways these two approaches treat data on imported commodities in intermediate production. The difference in consumption-based GHG emissions estimated using the two methods may reach approximately 20–30% for some countries (Peters, 2008; Peters et al., 2011a). Moreover, the differences in GHG emission associated with the bilateral trade balances calculated using the both approaches may attain approximately 50–60% or even had negative or positive GHG emission values embodied in the bilateral trade for the same country (Su and Ang, 2011). However, the MRIO approach produces additional uncertainties related to imported commodities. Because the sectoral use of commodities imported by countries–producers within the economy of a country–consumer is not available, the adjustment of import data brings uncertainties (Peters et al., 2011a; Wiedmann, 2009).

International trade data also deserve special attention. In the present study, data from the Eurostat datasets (Eurostat, 2010b,d) were used. The quality of these datasets is generally high but is heterogeneous among the EU27 countries (Eurostat, 2010e). Several types of uncertainties are also important in this area, including uncertainties related to the classifications applied in the IO tables and trade datasets, the methodology used to report trade data (i.e., all goods that cross the border of a country are recorded as imports; in a similar manner, all outgoing goods are included in exports) and the method used to convert trade data expressed in national currency into a common currency, the euro (i.e., monthly averages of daily exchange rates or annual exchange rates are used for different goods) (Eurostat, 2006). In addition, Lenzen et al. (2004) have listed trade-related uncertainties due to “time lags between shipping of export and receipt of imports, reporting errors, losses due to accident in transits”.

Perhaps most important to the total uncertainty in determining total consumption-based GHG emissions are issues related to optimal spatial disaggregation of the input data used in the consumption-based inventories (e.g., the IO tables, energy data, trade data, emission factors, and other data). To date, most studies have relied on country-average input data and emission factors. However, countries are diverse with respect to their primary and secondary fuel energy-mixes and technologies, technology processes and agricultural practices. Optimal disaggregation is especially important for large countries (e.g., China, the United States, Russia and Brazil), but small countries are not excluded (e.g., Slovakia, Estonia). Su and Ang (2010) present a good example of the difference in the total energy-related CO_2eq emissions in exports accounted for by spatial disaggregation. The authors showed that the CO_2eq energy-related emissions embodied in exports from China, a large country, based on an eight-region-model were approximately 14% lower than CO_2eq emissions estimated from country-level average data.

The understanding of uncertainty information is primarily needed in order to identify areas in which the inventory might need improvement. However, for further detailed and comprehensive development of a consumption-based GHG inventory that covers all GHGs released from all sources, the minimisation of uncertainties related to already available and used input data is not the only activity required. In particular, two sectors omitted from the study (i.e., the LULUCF and waste sectors), should be included in the analysis of GHG emissions. The consideration of non-energy-related CO_2eq emissions associated with the LULUCF sector could make a remarkable difference in the calculated balance of GHG emissions between production-based and consumption-based GHG inventories. For example, Gavrilova et al. (2010) showed that the annual ‘import’ of CO_2eq embodied in soybeans imported from Brazil and Argentina for use in Austria's livestock production was 1017 tCO_2eq due to deforestation in these countries, an emission source of the LULUCF sector. This particular import contributed more than 30% of the total CO_2eq emissions released due to domestic production of livestock and related products in Austria in 2000. Estonia also imported soybeans from Germany and the Netherlands (FAOSTAT, 2010), each of which imported crops from Brazil and Argentina. Although Estonia imported soybeans in lower amounts than Austria (e.g., 22,085 t versus 499,931 t by Austria in 2005), the non-energy-related CO_2eq emissions embodied in the soybeans exported from Brazil and Argentina to Germany and the Netherlands could change the emission balance of Estonia, perhaps to a lower degree than that of Austria. Estonia also imported beef from Brazil and Argentina, countries in which the production of beef is considered a driving force for deforestation (Zaks et al., 2009). Hence, accounting for non-energy-related GHG emissions embodied in beef imports from Brazil and Argentina would alter Estonia's GHG emission balance. The examination of non-energy-related GHG emissions associated with the waste sector would contribute less to the difference between the two GHG inventories than inclusion of the LULUCF sector. GHG emissions released from the waste sector make up approximately 2–10% of the total GHG emissions of a country (UNFCCC, 2010b), and the major quantity of GHG from the waste sector consists of emissions from municipal waste disposal. The latter could be directly considered under the consumption-based inventory because the emissions are associated with consumption.

The particular aspects of the energy, industrial processes and agricultural sectors that were omitted from the development of the method used in the present study to estimate energy-related and non-energy-related GHG emissions should eventually be addressed to make the consumption-based GHG inventory more complete, e.g., to include fugitive emissions due to the refining of petroleum products and solid fuel transformation, GHG emissions associated with the remaining (more than 30) products considered under the industrial processes sector and the agricultural sector (e.g., crops: legumes, fodder roots or dairy products such as butter and cheese). The estimation of GHG emissions due to the use of solvents and other products would be directly considered under the consumption-based inventory.

Undoubtedly, accounting for non-energy-related and energy-related GHG emissions will additionally require the development of currently absent large datasets. In particular, accounting for non-energy-related GHG emissions calculated under the land use change sectors would require the development of large datasets on the influence of production of particular commodities on changes in land use practices (e.g., deforestation). In addition, the use of other methodological approaches, e.g., full carbon accounting (Gavrilova et al., 2010), is also advisable. In the waste sector, the GHG emissions released due to industrial wastewater generation associated with manufactured products (e.g., food and beverages, pulp and paper) could be estimated based on the tonnage-output of the products produced and bilaterally traded. Furthermore, accounting for GHG emissions released due to industrial waste disposal would also require large datasets on the type of solid waste generated in the production of each commodity within a given year, permitting use of the first-order decay method in calculating the emissions from the landfills (IPCC, 2006). The estimation of energy-related and non-energy-related GHG emissions associated with the items omitted from the present study could be based on existing datasets on energy statistics (Eurostat, 2010c) or on records of products produced, imported and exported in physical terms recorded under the dataset of the Community Survey of Industrial Production (Prodcom, 2010). Moreover, the examination of all sources of energy-related and non-energy-related GHG emissions could be completed using both the EEBT and MRIO approaches. This allows the transparent analysis of GHG emissions associated with the bilateral trade balance and detailed examination, considering GHG emissions embodied in (re)exported commodities.

In summary, because the further development of the GHG inventory system is a very important tool in implementing successful action to mitigate human pressures on the climate system, all of the abovementioned steps should be taken in order to estimate GHG emissions in internationally traded commodities more accurately and to establish consumption-based GHG national inventories for Estonia and other countries.

Acknowledgement

We thank two anonymous reviewers for their constructive and useful comments.

Appendix A. Detailed methodologies

Energy-related emissions due to combustion of primary and secondary fuels, energy sector. The combustion of primary and secondary fuels to produce useful energy (i.e., electricity and thermal energy) and in vehicles results in emissions of CO_2, CO, CH_4 or NMVOCs and non-CO_2 gases (IPCC, 2006). Energy-related CO_2, CH_4 and N_2O emissions (converted to CO_2eq (IPCC, 1995); 'CO_2eq emissions' in this sub-section) associated with the production, bilateral trade and consumption of commodities of Estonia were estimated using IO analysis and basic methods of the 2006 IPCC Guidelines (IPCC, 2006).

The standard IO tables provide a detailed picture, in monetary terms, of the total output of commodities by each sector of the economy, the use of domestically produced and imported commodities of one sector for intermediate consumption to produce commodities in another sector of economy, the final consumption of commodities (i.e., domestically produced and imported) within the economy and exported abroad (Eurostat, 2008). Algebraically, the relationship between the total output of sectors and the intermediate and final demand for commodities can be described as follows (A1):

$$x = A \cdot x + y, \tag{A1}$$

where A is the matrix of intermediate consumption, which defines the intermediate input requirements for each commodity (domestically produced and imported) of each industry to produce one unit of commodity output in another industry (called the technology matrix), x is the vector of output and y is the vector of final demand (i.e., domestic and export). The solution of the linear equation system (A1) is (A2).

$$x = (I - A)^{-1} \cdot y \tag{A2}$$

In (A2), $(I - A)^{-1}$ is called the Leontief inverse matrix and reflects the direct and indirect requirements in commodities for intermediate consumption for the production.

To implement the estimations in the context of the EEBT approach, the standard IO tables should be transformed. Specifically, the requirements for imported commodities are usually removed from the system because they are investigated separately (Peters, 2008; Su et al., 2010). Hence, the rearranged Eq. (A2) will be as follows (A3):

$$x = (I - A_d)^{-1} \cdot y, \tag{A3}$$

where the Leontief inverse matrix $(I - A_d)^{-1}$ reflects only the direct and indirect requirements in commodities domestically produced for intermediate production.

The extension of the IO table with energy data and afterwards with CO_2eq emissions, calculated using the basic IPCC method (i.e., the quantities of primary and secondary fuels consumed, expressed in TJ-terms, were multiplied by emission factors that quantify CO_2eq emissions per TJ; IPCC, 2006) distributes the total energy consumption and CO_2eq emissions generated by a production–consumption system over different sectors for production of commodities (i.e., intermediate consumption) and final use. In other words, rows showing energy consumption and emissions, which are added to the monetary IO table, enable the estimation of a direct emission coefficient for each commodity, and the simultaneous calculation in the domestic Leontief inverse matrix provides the total emission coefficient (i.e., direct and indirect intensity) of each commodity.

Formally, the direct CO_2eq emission intensity of the production process of a commodity can be defined as $b_i = {}^{e_i}/_{x_i}$, where, e_i represents the emissions that occurred during the process to produce commodity x_i, and the economy-wide vector on direct emission can be expressed by b. The vector z incorporates the results for the direct and indirect CO_2eq emissions for the total output of commodities for all sectors (A4), as follows:

$$z = b \cdot (I - A_d)^{-1} \cdot y \tag{A4}$$

Hence, the direct and indirect CO_2eq emission intensity of a commodity can be expressed as $c_i = {}^{z_i}/_{x_i}$..

Due to the use of the EEBT approach, the assessment of CO_2eq emissions embodied in export is obvious given that the export is a part of the total final demand (y). Thus, if the total CO_2eq emission intensity of a commodity c_i is pre-multiplied by the export of that commodity i (ex_i), then CO_2eq emissions embodied in the export (j_i) can be expressed as follows (A5):

$$j_i = \sum\nolimits_1^g c_i \cdot ex_{ig} \tag{A5}$$

where g is a country of destination.

The total CO_2eq emissions embodied in the export of goods and services were calculated as follows (A6):

$$J = \sum\nolimits_i^n \sum\nolimits_g^n c_i \cdot ex_{ig} \tag{A6}$$

The total CO_2eq emissions embodied in import (Y) were assessed by the categories of commodities imported by a country of origin and the total CO_2eq emission intensity of these commodities. Mathematically, the relationship can be expressed as shown in (A7), in which the CO_2eq emissions embodied in the commodities of sector

(im_i) imported from country of origin g with the total emission intensity c_i were calculated.

$$Y = \sum_i^n \sum_g^n c_i \cdot im_{gi} \tag{A7}$$

The total CO_2eq emissions embodied in imports for further re-export were not considered because the emissions associated with re-export and embodied in import and export lead to a slight misunderstanding of the quantity of CO_2eq emissions imported to a country for consumption and those produced within a country and exported abroad. The total CO_2eq emissions associated with consumption of commodities in Estonia in 2005 was computed using the formula (1).

Standard IO tables for more than 40 countries[3] were employed to appraise the total CO_2eq emission intensities of the commodities (i.e., energy-related direct and indirect emissions). These included the 27 IO tables of the EU, comprising 59 commodities and developed by the Eurostat (Eurostat, 2010a), and the 15 IO tables of the non-EU27 countries developed by the OECD (2010), including data on 48 commodities. Because the IO tables of the EU27 and non-EU27 countries comprise different numbers of commodities, the IO tables were adjusted to conform to each other. Specifically, the numbers of commodities were aggregated or disaggregated into 42, which is considered to be sufficient to provide an analysis of the emissions embodied in traded commodities (Su et al., 2010). In addition, one assumption concerns only non-EU27 trade partners of Estonia: the reporting year selected for this study was 2005, but the IO tables were developed by the OECD for 2000–2003. It was assumed that no remarkable technological change occurred since 2000–2003 and that the total energy-related CO_2eq emission intensities had not altered.

Data on the energy use of 25 fuel types (e.g., hard coal, lignite, peat, crude oil, residual fuel oil, natural gas, biomass and biogas) were obtained from datasets of the Eurostat (2010c) and International Energy Agency (IEA, 2003a,b; 2005a,b). Because the industrial classification system applied in the IO tables and the classification of energy use by sectors of a country's economy are not the same (i.e., energy statistics are not detailed because the data on energy consumption is aggregated into 25 economic sectors), a correspondence between the two classification systems was made, which corresponds to approach 2 (i.e., data treatment scheme) defined by (Su et al., 2010). Specifically, the 'consumption of energy' data for 42 commodities were disaggregated in accordance with the classification established under the IO tables, taking into account the weight-share output of each commodity from the total output of sector.

Values of the emission factors for CO_2, CH_4 and N_2O for each type of fuel (t/TJ) from (IPCC, 2006) were used to estimate the direct and indirect CO_2eq energy-related emissions. The 2006 IPCC Guidelines provide values for emission factors by economic sectors in which fuels were combusted; these include the energy and manufacturing industries and the construction, commercial, agricultural, forestry and fishing sectors. Energy-related CO_2 emissions due to biomass combustion were considered as zero, according to the rules established by the 2006 IPCC Guidelines (IPCC, 2006).

The total CO_2eq emission intensities of 42 commodities from more than 40 countries were defined in tCO_2eq/1000€. The total CO_2eq emission intensities of the commodities produced in the countries (i.e., trade partners of Estonia) for which IO tables are not available were assumed to be the average of the emission intensities of non-EU27 countries.

The data on Estonia's bilateral trade in commodities, measured in monetary terms, were obtained from the Eurostat (2010b,d). A correspondence between the trade nomenclature and the industrial classification system applied in the IO tables was established.

Energy-related emissions, fugitive emissions, energy sector. Unintentional release of CH_4 and CO_2 can occur due to the extraction, processing, storage, transportation and distribution of fossil fuels (e.g., coal, oil shale, crude oil and natural gas; also known as primary fuels) to the final point of their use (IPCC, 2006). In addition, CO_2, N_2O, CO, CH_4, NMVOCs and non-CO_2 gases can be emitted in non-productive combustion activities, e.g., waste natural gas flaring at production and processing facilities. Fugitive emissions are also classified as energy-related emissions (IPCC, 2006).

Energy-related fugitive CO_2, CH_4 and N_2O emissions (converted to CO_2eq emissions (IPCC, 1995)) related to coal and oil shale mining, natural gas processing[4] (i.e., production, venting and flaring activities) and peat extraction activities[5] were considered in the present study. CO_2eq emissions due to transmission, storage and distribution of natural gas were omitted from the study.

Energy-related fugitive CO_2eq emissions ('CO_2eq fugitive emissions' in this sub-section) associated with the production, export and import of coal, peat and natural gas were estimated based on the quantities of primary fuels extracted, exported and imported (measured in tonnage- and energy-terms) and CO_2, CH_4 and N_2O emission factors (converted to CO_2eq) quantified CO_2eq emissions per t or TJ of primary fuel (i.e., tCO_2eq/t of coal/peat and tCO_2eq/TJ of natural gas).

CO_2eq fugitive emissions associated with the consumption of primary fuels were estimated using formula (1). Data on the production of primary fuels (i.e., coal, oil shale, natural gas and peat) in Estonia and on Estonia's bilateral trade by fuel type in physical terms (i.e., in t and TJ) from (Eurostat, 2010d) were used.

Emission factors related to coal and oil shale mining by different country–producers were obtained from the national tables of Common Reporting Format submitted to the UNFCCC (UNFCCC, 2010b). Emission factors related to peat production were computed based on areas transformed as a result of peat extraction and the amount of peat produced from these areas. The data were obtained from the national inventory tables (UNFCCC, 2010b) and from (Eurostat, 2010c). Emission factors associated with the extraction, venting and flaring of natural gas from the 2006 IPCC Guidelines (IPCC, 2006) were used.

Non-energy-related emissions from the industrial processes sector. Raw materials can be chemically and physically transformed from one state to another. The processes involved in such material treatment are associated with non-energy-related emissions of CO_2, CH_4, N_2O, HFCs and PFCs (IPCC, 2006).

The present study examined non-energy-related CO_2 and N_2O emissions (in CO_2eq emissions (IPCC, 1995)) released from manufacturing processes to produce cement, lime, glass, chemicals (i.e., nitric acid and ammonia) and iron and steel products. CH_4 emissions do not occur in the considered industrial processes.

Non-energy-related CO_2eq emissions associated with the manufacturing processes to produce the products were estimated based on the basic method presented in the 2006 IPCC Guidelines (IPCC, 2006), accounting for the quantity of the product produced in tonnage-terms and emission factors specified for each type of the product. The same algorithm was used to estimate CO_2eq emissions embodied in the product imported/exported. Formula (1) was employed to

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[3] The IO tables of the following countries were considered: the EU27 countries, Argentina (AR), Australia (AU), Brazil (BR), Canada (CA), China (CN), Indonesia (ID), Japan (JP), the Republic of Korea (KP), New Zealand (NZ), Norway (NO), Russia (RU), South Africa (ZA), Switzerland (CH), Turkey (TR) and the United States of America (US).

[4] Estonia does not produce, import or export crude oil. Thus, CO_2eq emissions associated with crude oil production and the emissions embodied in its trade were not included.

[5] CO_2eq emissions due to peat production are not considered fugitive emissions; these emissions are accounted for under the LULUCF sector of the national inventory. Nevertheless, the present study assessed CO_2eq emissions due to peat production together with fugitive emissions from coal, oil shale and gas production.

calculate the emission associated with the consumption of the products in Estonia.

The data on the amount of products produced in Estonia were obtained from Estonia's Common Reporting Format table (UNFCCC, 2010b). The data on amounts of products imported and exported to/from Estonia, measured in tonnes, by country-origin and country-destination were taken from (Eurostat, 2010d). CO_2 and N_2O emission factors (tCO_2, tN_2O/t of product) were employed from the 2006 IPCC Guidelines and from the national inventory tables (IPCC, 2006; UNFCCC, 2010b).

Non-energy-related emissions from the agricultural sector. Livestock farming and cropping activities result in emissions of CO, CH_4, NMVOCs, N_2O and NO_x (IPCC, 2006). This study considers non-energy-related CH_4 and N_2O emissions (converted to CO_2eq emissions (IPCC, 1995)) occurred due to crop production (cereals, rice and soybean) and associated with livestock keeping (i.e., emissions from enteric fermentation and due to manure storage and treatment).

The basic methods presented in (IPCC, 2006) were used to estimate the emissions related to the production, bilateral trade and consumption of crops, living animals (i.e., cattle, swine, sheep, goats, horses and poultry) and livestock-related products (i.e., beef, pork, mutton, poultry, goat and horse meat and cattle-milk).

CO_2eq emissions associated with crop production and embodied in bilateral trade were computed based on the quantities of crops produced and traded, in tonnage-terms, and emission factors, specifying the emission per tonne of crop type. Data on Estonian crop production and bilateral trade with crops by country-origin and country-destination, in tonnage-terms, were obtained from the Eurostat (2010d). Emission factors (tN_2O/t, converted to CO_2eq) were taken from (IPCC, 2006).

CO_2eq emissions associated with living livestock farming and with bilateral trade were estimated based on the number of livestock farmed in Estonia or traded with Estonia by category of animal and expressed in head-terms and N_2O and CH_4 emission factors (converted to CO_2eq), which quantify emissions per head of livestock category. The data on living livestock population farmed in Estonia, expressed in head-terms, were taken from Estonian Statistics (ESO, 2010), and the data on bilateral trade in living livestock categories were obtained from FAOSTAT (2010).

CH_4 emission factors (tCH_4/head/year) from livestock enteric fermentation and manure management were obtained from (IPCC, 2006) and disaggregated by livestock category, country and climate zone. N_2O emission factors (tN_2O/head/year) from livestock manure management were enhanced. In addition to N_2O emission factors per head of livestock category per year of manure management practice (disaggregated by country and climate zone), N_2O emission factors per head of livestock category due to the later application of manure on agricultural lands and the subsequent volatilisation (i.e., atmospheric deposition), leaching and run-off of nitrogen contained in animal manure were estimated.

Because CH_4 and N_2O emission factors were employed in the estimates to specify the quantities of CH_4 and N_2O emissions occurring per head of livestock per year, time-scaling factors (age-scaling) for the emission factors of several livestock categories were applied. It was assumed that the living livestock categories (i.e., pigs, goats, sheep and poultry) are not farmed for an entire year (the time period of the emission factors) but are sold after a certain period of time. Namely, pigs, goats and sheep are sold after 180 days, and poultry after 42 days. Time-scaling factors were not implemented for cattle and horses livestock categories.

CO_2eq emissions from the production of livestock-meat in Estonia were not estimated separately because the national statistics on livestock population already include the number of livestock slaughtered for meat production and the livestock newborn population (ESO, 2010). The data on the bilateral trade of livestock-meat, measured in tonnage-terms, were obtained from the Eurostat (2010d) and FAOSTAT (2010). CO_2eq emissions associated with the trade of livestock-meat were computed using the following algorithm: the quantity of meat by type of livestock imported by country of origin (in tonnes) was divided by the carcass-weight of the livestock category in each country (t/head; FAOSTAT, 2010), allowing the estimation of the livestock population slaughtered for meat production in the country exporting to Estonia, for which the emission factors (i.e., CH_4 and N_2O; corrected with the abovementioned time-scaling factors) were applied.

CO_2eq emissions from the production of fresh cattle-milk in Estonia were not estimated separately because the emissions released from dairy-cattle farmed in Estonia included the quantity of emissions associated with cattle-milk production. To estimate CO_2eq emissions associated with cattle-milk imported and exported to/from Estonia, in tonnage-terms, milk yields per dairy-cattle head per year (t milk/head/year) in each trade partner were employed from (FAOSTAT, 2010). This permitted calculation of the number of dairy-cattle population producing milk in each country for the trade; this number was multiplied by the emission factors specified for each country. The present study focused only on fresh cattle-milk, and non-energy CO_2eq emissions associated with bilateral trade of cattle-milk-related products (e.g., cream, cheese, and butter) were not evaluated.

Appendix B. Economic sector and commodity classification

Table B.1
Classification of the main economic sectors, commodity produced by the sectors, and their identification numbers.

Nr	Sector of the economy	Nr	Commodity (i.e., goods and services) produced by the sector
1	Fuel extraction industry	1	Mining and quarrying (energy) products
2	Coke, refined petroleum products industry	2	Coke, refined petroleum products and nuclear fuels
3	Electrical energy and thermal energy generation industry	3	Electrical energy
		4	Steam and hot water; collection, purification and distribution of water
4	Iron and steel industry	5	Basic metals
5	Non-ferrous metal industry	6	Fabricated metal products, except machinery and equipment
6	Chemical industry	7	Chemicals, chemical products and man-made fibres
		8	Rubber and plastics products
7	Non-metallic mineral products industry	9	Other non-metallic mineral products
8	Ore extraction industry	10	Mining and quarrying (non-energy) products
9	Food, drink and tobacco industry	11	Food products, beverages and tobacco
10	Textile, leather and clothing industry	12	Textiles, textile products, leather and footwear
11	Wood and wood products, paper and printing industry	13	Wood and products of wood and cork
		14	Pulp, paper, paper products, printing and publishing products
12	Engineering and other metal industries	15	Machinery and equipment
		16	Office, accounting and computing machinery
		17	Electrical machinery and apparatus
		18	Radio, television and communication equipment
		19	Medical, precision and optical instruments
		20	Motor vehicles, trailers and semi-trailers
		21	Other transport equipments
		22	Other equipments
13	Agriculture, hunting, forestry and fishing	23	Agriculture, hunting, forestry and fishing
14	Transport sector	24	Land transport; transport via pipelines
		25	Water transport
		26	Air transport
		27	Supporting and auxiliary transport activities; activities of travel agencies

Table B.1 (*continued*)

Nr	Sector of the economy	Nr	Commodity (i.e., goods and services) produced by the sector
15	Commercial sector	28	Construction work
		29	Wholesale and retail trade; repairs
		30	Hotels and restaurants
		31	Post and telecommunications
		32	Finance and insurance
		33	Real estate activities
		34	Renting of machinery and equipment
		35	Computer and related activities
		36	Research and development
		37	Other business activities
		38	Public administration and defence; compulsory social security
		39	Education
		40	Health and social work
		41	Other community, social and personal services
		42	Private households with employed persons

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Teised professionaalsed tegevused	
2009 –	Kasvuhoonegaaside inventuuride ja muu informatsiooni, mis on esitatud Lisa I riikidega, tehniline audit
2007 –	Eesti kasvuhoonegaaside heitkoguste inventuuri koostaja IPCC Juhendite alusel (esitatakse ÜRO sekretariaadile ja EK komisjonile)
Teadustöö põhisuunad	Keskkonna-ökonoomika, süsinikuringe, aine voogude analüüs, elukaare analüüs

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