# ENERGY EFFICIENCY OF RAPESEED BIOFUEL PRODUCTION IN DIFFERENT AGRO-ECOLOGICAL SYSTEMS

Melese Tesfaye Firrisa March, 2011

Course Title:	Geo-Information Science and Earth Observation for Environmental Modelling and Management
Level:	Master of Science (MSc)
Course Duration:	September 2009 – March 2011
Consortium Partners:	University of Southampton (UK) Lund University (Sweden) University of Warsaw (Poland) University of Twente, Faculty ITC (The Netherlands)

# Energy Efficiency for Rapeseed Biofuel Production in Different Agro-Ecological Systems

By

Melese Tesfaye Firrisa

Thesis submitted to the University of Twente, faculty of ITC, in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation for Environmental Modelling and Management

Thesis Assessment Board

Chair:	Dr. Y. A. Yousif Hussin
External Examiner:	Prof. P. Petter Pilesjö
First Supervisor:	Ms. Dr. I. C. Iris van Duren
Second Supervisor:	Dr. Alexey Voinov



# Disclaimer

This document describes work undertaken as part of a programme of study at the University of Twente, Faculty of ITC. All views and opinions expressed therein remain the sole responsibility of the author, and do not necessarily represent those of the university.

#### Abstract

Due to increasing concerns related to fossil fuels use and problems with their supply, the use of alternative sources of energy is increasing these days. One of these alternative sources is biomass used to produce biofuels. European Union has implemented a biofuel directive, which requires the use of biofuels in transport sector. As the use of biofuels is increasing, it becomes increasingly important to study their feasibility and efficiency. One of the crops in Europe used for biofuel production is rapeseed. In this study we focused on rapeseed production for biodiesel and; compared the energy efficiency in terms of Energy Return On Energy Invested (EROEI) for two EU countries (Poland and The Netherlands) using the Life Cycle Assessment (LCA) methodology. Life Cycle Inventory (LCI), as a phase of LCA, was implemented for the two countries accounting for inputs, processes and outputs of energy in the rapeseed methyl ester (RME) production system. A thorough literature review was conducted and farmers in both countries were interviewed. Using the two countries as a reference study and incorporating other statistical and biophysical data, mapping of EROEI over the whole Europe was carried out. Due to differences in agro-ecological and production systems the EROEI values range between 1.51-2.75 in Poland and 2.15-2.93 in the Netherlands. This indicates that rapeseed biodiesel production system in The Netherlands is more efficient than in Poland when straw, meal and glycerine are included in LCI system boundary. Based on these studies we calculated an average in Europe and conducted spatial analysis of EROEI across Europe. This gave maximum EROEI value of 2.52 at maximum attainable yield of 5.52 ton/ha. For the majority of EU countries the EROEI value is 1.24-2.32. More than 26% of the total area in Europe can produce rapeseed biofuel only with an energy loss. The research indicated that unless there are some major technological improvements in rapeseed production and processing, in EU, which can increase the efficiency of biodiesel production in supplementing fossil fuels by biofuels is not a feasible option. Down-scaling the spatial analysis and using high resolution data (spatial, temporal and system boundary refining) are recommended in understanding and improving the analysis for given localities.

### Acknowledgements

God deserves the most! "Your decrees are the theme of my song wherever I lodge". Thank you! You are with me all the time and made me to pursue my course in here. I am very much indebted to my supervisors Dr. Iris van Duren and Dr. Alexey Voinov for their academic support from the very conception of the research idea to the end of the write up. Your supervision goes more than reading my writings. Some of them worth mentioning are your scientific idea input, participation in my field work, good wishes during my journey for the same purpose and so on. I feel being privileged in knowing and working with you!

I am thankful to European Union for provision of Erasmus Mundus scholarship and hosting universities (Southampton, Lund, Warsaw and ITC of Twente) for their loving care and contemporary educational platform. Beyond getting diversified educational experiences from different academia of these Universities, the input from cultural adventure and being together with international students surpasses words. Thank you for such of your investment!

My heartfelt gratitude goes to the following individuals who made this writing real. They are rapeseed farmers and those in one way or another provided me data, information and communicated through e mail at time of my need; they were there for me. Jan Smorawski, Jerzy Dolat, Szymom Kuczynski, Tadeusz Jakubowski, Wiesiaw Gryn, Henryk Filas, Beltman, Hein Bakker, Antoon Kleverkamp, F. Vervoort, H. Titulaer, Mirella Salvatore, Gerard Meuffels, Joep Hermans, David Rossiter, Eric Smaling, Robert Gmyrek, Freddy Nachtergaele, Harrij Tonco van Velthuizen, Willem van Geel, Marc Van Liedekerke, Sascha .R. A. Kersten, Antoon Kleverkamp, Panos Panagos, Małgorzata Tomankiewicz, Gerard Reinink, Janneke Ettema, Joanna Maciejewska, Szymon Kuczynski, and Ilona Kaandorp, thank you very much!

My co- Geo-Information Science and Earth Observation for Environmental Modelling and Management (GEM) students and friends of such a time of being together for eighteen months, I very much thank you for your support, and sharing your experience with me. GEMers you are great friends! My special thanks goes to my father Tesfaye Firrisa, brother Yidnekachew Tesfaye, his wife Abebech and his baby boy Yedidiya, younger brother Dagnachew Tesfaye and relatives back home for their love and prayer during my stay abroad for this study. We made it together!

I am very much grateful of my girlfriend, Joanna Sopyło, for her love, prayers and support during all my ups and downs. She served as a translator while I was interviewing Polish farmers and part of the research this way. Kocham Cię!!

All, whom I did not mention but got part in those days of study, thank you very much!

# Table of contents

Abstract		i
Acknowle	dgements	ii
List of Fig	ures	v
List of Tal	bles	vi
List of Ap	pendices	vii
List of Ab	breviations	viiviii
1. INTI	RODUCTION	1
1.1.	The need for energy and energy use	1
1.2.	Concerns related to fossil fuels	1
1.3.	Alternative energy sources and biofuels	2
1.4.	Rapeseed biofuel production in Europe	2
1.5.	Concerns related to biomass for biofuels production	4
1.6.	Importance of energy efficiency in biofuel production	4
1.7.	Energy return on energy invested and life cycle assessment	5
1.7.1	. Energy Return on Energy Invested (EROEI)	5
1.7.2	History, use and application of Life Cycle Assessment	7
1.8.	Objectives and research questions	10
1.8.1	. Objectives	10
1.8.2	Research questions	10
1.9.	Study context and conceptual framework	11
2. MET	HODOLOGY	13
2.1.	Study area description	13
2.2.	Procedures and flow chart of the research	13
2.3.	Data used and analysis	13
2.3.1	. Life cycle inventory and EROEI estimation	14
2.3.2	Potential rapeseed area mapping	15
2.4.	Life cycle inventory methodology and assumptions	17
2.4.1	. Goal of the study	17
2.4.2	Scope of the study: functional unit and system boundaries	17
2.4.3	. Data collection methods	18
2.4.4	Computational model	19
2.4.5	Energy efficiency computation	22
2.5.	Methodology used in mapping of EROEI	23
3. RES	ULTS	27
3.1.	Interview result	27
3.2.	Rapeseed farming system characteristics	
3.2.1	. Poland	

3.2.2	2. Netherlands	29
3.3.	Biofuel production feature	29
3.4.	Life Cycle Inventory	30
3.4.1	. Unit processes	30
3.4.2	2. Results of calculation procedures	30
3.4.3	B. Energy allocation	34
3.5.	Energy Returned on Energy Invested	
3.6.	Energy efficiency gradient across Europe	
3.6.1	. Reclassified Global Agro-Ecological Zones map	
3.6.2	2. Map of rapeseed yield	
3.6.3	8. Map of Energy Return On Energy Invested	
3.6.4	Country based yield and EROEI from EROEI gradient map.	
4. DISC	CUSSION	43
4.1.	Rapeseed biofuel production system and EROEI	43
4.2.	Impacts of different inputs on energy efficiency	44
4.2.1	. Yield	44
4.2.2	2. Fertilizers	
4.2.3	6. Oil extraction	46
4.2.4	Biodiesel production	46
4.2.5	5. Other inputs and processes	47
4.3.	Impacts of different products on energy efficiency	
4.3.1	. Meal	
4.3.2	2. Glycerine	
4.3.3	S. Straw	
4.4.	Energy efficiency indication using EROEI	
4.5.	Energy efficiency gradient over Europe	
4.6.	Regional and country based EROEI	50
4.7.	Implication of EROEI value from different yield sources	51
5. CON	ICLUSION AND RECOMMENDATION	
6. REF	ERENCES	61
7. APP	ENDICES	67

# **List of Figures**

v

# List of Tables

Table 1. Biodiesel production in Poland and The Netherlands4
Table 2. Suitability classes given by Global Agro-Ecological Zones (GAEZ)23
Table 3. Literature used for the study on biodiesel production from oilseed rape24
Table 4. Input and processes from interview and their quantities per hectare in both
countries and Europe
Table 5. Energy required (MJ/ha) for different rates of fertilizer for each countries
and over Europe
Table 6. Energy required (MJ/ha) for different crop protection chemicals in case
study areas and over Europe
Table 7. Energy required (MJ/ha) for transportation
Table 8. Energy required for the conversion the feedstock to final product
Table 9. Energy value (MJ/ha) of different co- and by-products
Table 10. Energy value (MJ/ha) of Rapeseed Methyl Ester (RME)34
Table 11. Input and output energies (MJ/ha) for different activities, processes and
inputs
Table 12. Primary Inputs and output energies with respective EROEI value
Table 13. Different EROEI values under different considerations 38
Table 14. Area of different suitability classes and their corresponding yield and
EROEI range
Table 15. Percent contribution of each input energy 55
Table 16. Yield and EROEI relation 56
Table 17. Energy contribution of different products per hectare of rapeseed produced
Table 18. Area and percentage of area with particular EROEI value ranges57
Table 19. European countries under the three scenarios 57

vi

# List of Appendices

Appendix 1. Interview format for farmers in Dutch	.67
Appendix 2. Interview format for farmers in Polish	.72
Appendix 3.Country based EROEI map analysis	.78
Appendix 4. Average maximum and minimum yield and EROEI of each country i	in
Europe from yield and EROEI maps	.81

# List of Abbreviations

Aver	Average	
CIA	Central Intelligence Agency	
EJ	Exajoule	
EROEI	Energy Return on Energy Invested	
EU	European Union	
FAO	Food and Agricultural Organization	
GAEZ	Global Agro-Ecological Zones	
GHG	Green House Gas	
ha	hectare	
HHV	higher heating value	
ISO	International Organization for Standardization	
К	Potassium	
kg	Kilogram	
km	Kilometer	
LCA	Life Cycle Analysis	
LCI	Life Cycle Inventory	
Min	Minimum	
MJ	Mega Joule	
Max	Maximum	
Ν	Nitrogen	
NPK	Nitrogen, Phosphorus and Potassium	
Р	Phosphorus	
REPA	Resource Environmental Profile Analysis	
RME	Rapeseed Methyl Ester	
SETAC	Society of Environmental Toxicology and Chemistry	
t	tonnes	
UNEP	United Nations Environmental Program	

viii

# 1. INTRODUCTION

#### 1.1. The need for energy and energy use

Mankind is using energy in many ways to improve its living standards. The world energy consumption is increasing, which is related to growing population and consumption. Energy consumption is predicted to increase from 497 EJ in 2006 to 715 EJ in 2030. This 44% increase is leading to increase in GHG emissions (Cherubini and Strømman, 2010). Cherubini *et al.* (2009) estimate that bio-energy supplies 10% of the total world primary energy, which in most cases is used in the residential sectors for domestic purposes like heating and cooking. Energy is important because it is also correlated with gross products, labour productivity and price levels (Cleveland *et al.*, 1984), which shows that energy is the driving force to economic development. Fossil fuels are the main energy sources that drive the world economy.

# 1.2. Concerns related to fossil fuels

The sustainability of fossil fuel supply is in question because it is non-renewable. Below we summarize some of the reasons why relying on fossil fuels is risky (Ajanovic, 2010, Rockwell, 2011, Arvidsson *et al.*, 2011, Batchelor *et al.*, 1995, Baka and Roland-Holst, 2009):

- They are non renewable energy sources
- Currently fossil fuel use is by far faster than their rate of formation
- As reserves shrink, extracting fossil fuels becomes more difficult and eventually becomes cost ineffective
- There are always environmental and human costs involved in extraction and production of fossil fuels
- Fossil fuel consumption produces greenhouse gas (GHG) emissions
- Much of fossil fuels have to be imported from politically unstable countries, making their supply unreliable.

#### 1.3. Alternative energy sources and biofuels

These problems with conventional fossil fuels draw our attention to alternative energy sources (Arvidsson *et al.*, 2011), whereby biofuel energy is one of them. Alternative energies are considered as an option in mitigating climate change while reducing dependence on fossil fuel. Solar energy, wind energy, energy from water and biomass energy (bio-energy) are some of the alterative energies well known (Cherubini and Strømman, 2010, World Energy Council, 2010). Compared to fossil fuels, these alternative energy sources are beneficial in terms of environmental impacts, energy security and socio-economic externalities (Bomba *et al.*, 2007, European Biodiesel Board, 2003-2009b, EurActiv Network, 2009, McAlister and Horne, 2009, Cherubini *et al.*, 2009, Nanaki and Koroneos, 2009). Biofuels are derived from plants, and can be used directly for heat, electricity production or converted to liquid fuel (Davis *et al.*, 2009). Currently they are the only alternative to liquid fossil fuels and are produced from biomass (Cherubini and Strømman, 2010, Halleux *et al.*, 2008).

Though carbon neutrality of biofuels is questionable, they certainly decrease dependence on oil-producing regions and can help generate new income for farmers (Zah et al., 2009, Davis et al., 2009). Bureau et al. (2009) indicate that over recent years, biofuel production has being increasing. Worldwide major crops for biofuel production are corn, wheat, barley, sugarcane, rapeseed, oil palm, soybean, sugar beat, potato and sunflower (Ajanovic, 2010, Davis et al., 2009, Demirbas, 2008). A major controversy is that biofuel production relies on the same crops that can be used for food production (Baka and Roland-Holst, 2009, Kavalov, 2004). This increases food price and has indirect impact on land use and biodiversity (Nanaki and Koroneos, 2009, EurActiv Network, 2009, McAlister and Horne, 2009, Smith, 2007, Netherlands Environmental Assessment Agency, 2010, Arvidsson et al., 2011, Crutzen et al., 2008). The chemical compounds produced from these crops are: biodiesel, ethanol, methane and methanol (Brecha, 2008, Börjesson and Tufvesson, 2009, Ajanovic, 2010). "Biodiesel is a renewable fuel produced from vegetable oils such as rapeseed oil, sunflower seed oil, soybean oil and also used frying oils (UFO) or animal fats" (European Biodiesel Board, 2003-2009b, Kavalov, 2004).

# 1.4. Rapeseed biofuel production in Europe

European Union was the world leader of biodiesel and third in biofuel production in 2005 (Baka and Roland-Holst, 2009). Out of the total of 10.2 billion litres of biodiesel product worldwide in 2007, 60% was produced in the European Union. Rapeseed is one of oil crops (Ajanovic, 2010), which is mostly grown in Europe (VROM, 2010, Baka and Roland-Holst, 2009) accounting for more than half of the

production (Bureau *et al.*, 2009). In 2008 in Europe, 79% of all feedstock crops used for biodiesel production originates from rapeseed (Ajanovic, 2010). It is cultivated in most European countries (Purdue University, 2010, Thamsiriroj and Murphy, 2010). Rapeseed production positively affects the yield potential of subsequent crops (Braschkat, 2003) by increasing fertility of soil.

In Figure 1 and Figure 2 we show FAO crop statistics (2010), for Poland and The Netherlands (used as case studies below) for rapeseed yield (tonnes/ha) and area (ha).



Figure 1. Rapeseed yield of in Poland and the Netherlands (FAO, 2010)



Figure 2. Rapeseed area cover in Poland and the Netherlands (FAO, 2010)

Biodiesel production in these two countries given in Table 1 (European Biodiesel Board, 2003-2009a).

Country	Production ('000 tonnes) in year	
Country	2009	2010 <sup>1</sup>
Poland	332	710
The Netherlands	323	1036

Table 1. Biodiesel production in Poland and The Netherlands

Rapeseed is being produced primarily with the ambitious goal of reducing of GHG emissions with less consideration of the underlying effects and benefits in terms of energy efficiency and environmental considerations. In Europe, "support for biofuel production reached USD 4.5 billion in 2006" only (Bureau *et al.*, 2009). Such economic subsidies only blur the picture for real efficiency of biofuel production. Every biomass for biofuel production has got limitations.

### 1.5. Concerns related to biomass for biofuels production

There are controversial views about biofuel production in terms of environmental impacts and benefits (Ajanovic, 2010). How and where various agricultural technologies and inputs are applied can affect yield and the energy efficiency of biofuel production (Börjesson, 2008, Johnston *et al.*, 2009). According to Cherubini *et al* (2009), an ideal energy crop:

- 1. has efficient solar energy conversion resulting in high yield
- 2. needs low agricultural inputs
- 3. has low water requirements
- 4. has low moisture level at harvest

Finding crops that satisfy all these criteria is hard (Cherubini *et al.*, 2009). It is also stated that implementing new technologies in agriculture as well as in industrial processing is always an opportunity in improving biodiesel fuel life cycle energy efficiency (Janulis, 2004).

### **1.6.** Importance of energy efficiency in biofuel production

Different agricultural systems have different energy returns. Generally, there is higher fossil energy input for production of transportation biofuel from oil or starch crops than for biomass-derived electricity/heat generation, which usually comes from wood combustion. This is because of the former requires higher cultivation

<sup>&</sup>lt;sup>1</sup> Production capacity

inputs and involves more energy intensive stages in processing (Cherubini and Strømman, 2010, Hall and Day, 2009). Different studies come out with different assessments of net energy balance of biofuels. These variations are explained by the degree to which particular inputs are accounted for and the way fossil energy consumption is allocated to the various co-products that various production systems have (Bureau et al., 2009). These and other issues of energy assessment are even site specific (Cherubini et al., 2009). Energy efficiency is most often discussed together with sustainability analysis (Börjesson, 2008). Different agro-ecological areas do have different agronomic practices (Cherubini et al., 2009) and biophysical factors, which in turn influence the intensity of biomass production. Obviously, studying the energy efficiency of a system under different agro-ecological and agricultural practices for biofuel production has a vital role in applying the technology in an appropriate environment in relation to EROEI, which is an energy efficiency indicator discussed below. Agro-ecological system is referred to agricultural ecosystem and practices undergone in such ecosystems for agricultural production. Increasing energy efficiency is one of the contributing factor in reduction of the world GHG emission (Halleux et al., 2008).

### 1.7. Energy return on energy invested and life cycle assessment

#### 1.7.1. Energy Return on Energy Invested (EROEI)

Production of any biofuel is a work process as stated by Cleveland *et al* (1984), in which materials (feedstock crops) are concentrated, refined and otherwise transformed at free energy costs (Cleveland *et al.*, 1984). Energy return on energy investment (EROI or EROEI), which is a measure of energy efficiency, is calculated from the following equation (Cleveland, 2008, Mulder and Hagens, 2008, Hall *et al.*, 2009):

$$EROEI = \frac{\text{Energy returned to society}}{\text{Energy required to get that energy}}$$

EROEI less than one is considered to be 'unsustainable' energy production process (The Offshore Valuation Group, 2010). Hall *et al.* (2009) calculated the minimum EROEI to be 3:1 in order to support continuing economic activity and social function (Hall *et al.*, 2009). The "true value of energy for the society" (Odum, 1974), which is indicated as "central" to consider energy as value (Mulder *et al.*, 2010), from any source is decreasing through time because of the increase in energy investment in all the sub-systems of its production. Energy tapping from renewable resources is a function of land, labour, water, raw materials and others (Mulder *et al.*, 2010), which by themselves need input energy. Thus, energy is one of the

limiting input variables into bio-energy production (Mulder *et al.*, 2010) in type (Börjesson, 2008) or quantity. Different energy production technologies have different EROEI values, example offshore renewable (wind and wave) with high EROEI and fossil fuel with lower value (The Offshore Valuation Group, 2010). Also within a given technology the EROEI varies (Cherubini *et al.*, 2009) according to production environment and methodology (Chiaramonti and Recchia, 2010). The equation is simple, "although the devil is in the details" (Hall *et al.*, 2009). This is because; the energy input and output are all different in different technologies, besides energy comes in different qualities, which may be hard to compare. EROEI analysis is "highly sensitive to assumptions about both system boundaries and key parameter values" (Farrell *et al.*, 2006). Nevertheless the EROEI approach is based on solid thermodynamic principles and is important to understand the efficiency of energy production.

Mulder and Hagens (2008) classify the level of EROEI analysis as 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> orders EROEI. First order EROEI deals only with direct energy and non-energy inputs and direct energy outputs. It misses many critical energy inputs (example steam energy) and ignore co-products, which makes it superficial, yet it is the least controversial form of energy efficiency analysis. The second order EROEI analysis includes indirect energy and non-energy inputs and co-products into the analysis which requires critical energy allocation method and defining of boundaries to include indirect inputs.

Third order EROEI analysis incorporates additional energy costs for externalities of the energy production system and is considered to be the most accurate (Mulder and Hagens, 2008). External costs are energy costs allocated for any negative effects due to production system implemented. The accuracy and level of consensus around the value of different EROEI levels is shown in Figure 3.

Considering rapeseed biofuel production in line with the different EROEI accounting methods, first order EROEI includes energy input from cultivation, transportation and energy for conversion of the feedstock at refinery. The direct energy output is Rapeseed Methyl Ester (RME) produced. Second order EROEI calculation includes indirect energy inputs and energy cost of other products like by-and waste products in addition to what is included in the first order EROEI. The third level EROEI adds the negative impacts of the whole production system on the society and environment. It then allocates energy values to them in addition to what is included in the second EROEI level calculation. Rapeseed biodiesel production system has an EROEI value of 5.4 and 8.7 in north Europe calculated from rapeseed only and rapeseed including straw, respectively (Börjesson and Tufvesson, 2009).

To take into account the various processes and stages involved in biodiesel production Life Cycle Assessment (LCA) is a promising tool (Davis *et al.*, 2009). System boundaries are discussed below in chapter 3.



Figure 3. Relationship between precision and accuracy of different EROEI levels (Mulder and Hagens, 2008)

### 1.7.2. History, use and application of Life Cycle Assessment

LCA stands for Life Cycle Assessment though it was interchangeably used with terms like: eco-balance, cradle-to-grave analysis and life cycle analysis in previous studies (Horne, 2009). Historically, the late 1960s Resource Environmental Profile Analyses (REPAs) were the forerunners of the modern LCA. Major advancements in LCA methodology (Horne, 2009) came during the oil shortage of 1970s, which led to focus on energy analysis, and the spread of multi-criteria systematic inquiry in mid 1980. In the 1990s the term Life Cycle Assessment was coined at workshop in Vermont (USA) held by the Society of Environmental Toxicology and Chemistry (SETAC) and in the 2002 Life UNEP/SETAC Cycle Initiative by United Nations Environment Program (UNEP) and SETAC further contributed to LCA.

The widespread development of LCA is mainly due to increase of "consumers' interest in the world behind the product they buy" (Horne, 2009, Fava, 2002). According to the International Organization for Standardization (ISO), LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by:

- compiling an inventory of relevant inputs and outputs of a product system;
- evaluating the potential environmental impacts associated with those inputs and outputs; and

• interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study (ISO, 1997).

LCA is mostly used as a quantitative tool in relation to issues of production and consumption supporting and improving decision making (Clark and Leeuw, 1999, Davis *et al.*, 2009). It has been used in business, physical sciences and engineering disciplines, United Nations environmental projects, industry, government and NGOs (Horne, 2009, Clark and Leeuw, 1999).

Life Cycle Assessment studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences (ISO, 1997). According to ISO (ISO, 1997), the LCA standard includes: *Goal and Scope* definition of an LCA study, development of *Life Cycle Inventory* (LCI), Life Cycle *Impact assessment* and *Interpretation* (Fig 4). Devis *et al* (2008) defined LCA as computational tool for assessing the efficiency of energy systems to biofuel feedstock crops. Janulis (2003) stated that life-cycle energy balance depends on specific climatic conditions and agro- and processing technologies used (Janulis, 2004).

Proper framing of "key questions" formulates the definition of Goal and Scope including the setting of the functional unit. Scope is the identification of entire production and disposal or recycling process of material, components involved, inputs to the components and inputs, outputs, emission and wastes at all stages. Whereas, "inventory is the result of compiling all environmental flows, including resource use inputs and waste or pollution outputs" (Horne, 2009).

LCI is one of the components of LCA (ISO, 1997) and is basically a list of components that are included as a part of the system that is assessed in an LCA (Davis *et al.*, 2009). It clarifies the required inputs and outputs to be calculated in each steps of the production chain. Different LCIs include different components to be calculated based on system boundary. Differences in LCA assumptions about efficiency terms, life-cycle inventory components and system boundaries are the main factors generating variation in LCA results. The LCI influences the result of LCA by depicting the weights of different components (Davis *et al.*, 2009).

The relative advantage of LCA depends on the use of different input data, functional units, allocation methods, reference systems and other assumptions (Thamsiriroj and Murphy, 2010). Wide range of final LCA results are also due to uncertainties and use of specific local factors for indirect effects (Cherubini and Strømman, 2010).

LCA is considered to be good for environmental impact assessment, risk analysis and technology assessment. It has got key role in environmental management, policy and planning (Horne, 2009). Most LCA studies depend entirely on literature (Batchelor *et al.*, 1995), which makes this research different in interviewing farmers for feedstock extraction case.



Figure 4. Phases of Life Cycle Assessment (ISO, 1997)

# 1.8. Objectives and research questions

# 1.8.1. Objectives

# **General Objective**

Assessment of the energy efficiency in terms of EROEI of rapeseed biofuel production under different agro-ecological conditions and agricultural practices

# Specific Objectives

- Characterization of rapeseed biofuel production:
  - 1. Identifying local specifics of rapeseed production for different locations using life cycle assessment methods. Case studies in Netherlands and Poland
  - 2. Define the energy cost (value) of possible yield-enhancement strategies (fertilizers, manure, melioration, etc.)
- Producing life cycle inventory (LCI) data and developing EROEI model for rapeseed biofuel production in Europe
- Estimation of EROEI of rapeseed biofuel production under different agroecology and agricultural practices
- Determining and mapping of rapeseed biofuel energy efficiency over Europe across various agro-ecological systems

# 1.8.2. Research questions

The research was designed in a way that the following research questions tackled for the benefit of target groups of researchers, farmers, biofuel producing industries and policy makers.

- What are the components of rapeseed biofuel production processes, which involve energy as input and output?
- What are the energy values of these components?
- How is the current energy efficiency of rapeseed production for biofuel in different agro-ecologies and cultural practices in terms of EROEI?
- What is the influence of different agricultural practices on EROEI?
- How and where can we maximize energy efficiency in production of biofuel from rapeseed?
- Where is rapeseed biofuel production system being energetically efficient over Europe?
- Where in Europe does energy production from rapeseed make most sense in terms of energy efficiency?

• What are the implications of EROEI values?

# **1.9.** Study context and conceptual framework

The research was focused on calculating and estimating of energy efficiency in terms of EROEI in different agro-ecological contexts. Additionally, it was focused in investigating the sources of difference in energy efficiency starting from feedstock extraction to the production of rapeseed biofuel. Basically, the research has got two parts.

- 1. Detail analysis of EROEI between two countries of Europe: Poland and The Netherlands. This was primarily done using survey in interview form and literature review in Life Cycle Inventory (LCI) for material, energy and process analysis.
- Estimation of EROEI based on yield of rapeseed production, which depends on different agro-ecological and physical parameters. Maximum yield of 5.2 ton/ha attained in 1980 was used for estimation of EROEI using average model developed from LCI analysis in Poland and The Netherlands and finally for mapping. EROEI was calculated using LCI methodology.

The following figure shows the conceptual approach used in the study.



Figure 5. Conceptual approach used in the research

The research was designed in a way that field works for interviewing farmers and literature reviews are used thoroughly. At LCI phase, energy related issues of cultivation, oil extraction and biodiesel production in Poland and The Netherlands are found out through interviews and literature review. Energy efficiency in terms of EROEI of the two countries was calculated from LCI result. The model developed for the EROEI calculation was also used in EROEI mapping across Europe. Suitability map of oil crops was changed to yield estimation which was used in the model for mapping purpose (Figure 5).

# 2. METHODOLOGY

### 2.1. Study area description

The research comes in two parts. First we consider two European countries, Poland and Netherlands, for the comparison of current energy efficiency in terms of EROEI of rapeseed biofuel production. This assessment also helped in developing the method and model to calculate EROEI with due consideration of inputs, outputs and processes of production in both countries. The two countries were selected for the fact that they have different agro-ecology, agricultural production approach and being the two most rapeseed and biofuel producing countries in Europe (CIA, 2010a, CIA, 2010b) (Figure 6). The second part of the research is mapping of Energy Return on Energy Invested (EROEI) for the whole Europe. Twenty seven current member countries of the European Union and Switzerland were included for this purpose (Figure 6).

### 2.2. Procedures and flow chart of the research

The research was started by choosing study area (Figure 6). Data were collected based on their purpose over the study area, which include interview and literature review for Life Cycle Inventory and suitability map for EROEI mapping. Based on LCI data collected, EROEI model was developed for the case areas in Microsoft Excel spreadsheet and Vensim software for casual loop diagram making. The model constitutes three subsystems, which are feedstock extraction system, feedstock transportation and conversion of feedstock to biodiesel. Suitability data is reclassified in order to merge unsuitable areas, undefined data sets and water bodies into one class called unsuitable area using ArcGIS software. The reclassified suitability data was assigned with respective yield value using FAO maximum yield value over twenty years as maximum attainable yield. EROEI model developed for individual case study areas were used to develop EROEI model over Europe using yield as dependent variable. Each yield classes from yield map were used in the extrapolated EROEI model for mapping of EROEI over Europe. Country based EROEI was analysed in ArcGIS interface (Figure 5 and Figure 7).

### 2.3. Data used and analysis

Farmers' interviews and literature were the main sources of data for rapeseed biofuel energy efficiency assessment study. Global Agro-Ecological Zones (GAEZ) (Fischer *et al.*, 2002) geo-data are used for EROEI mapping. Data and sources of data are described as follows.



Figure 6. Case study and EROEI mapping areas

### 2.3.1. Life cycle inventory and EROEI estimation

In order to collect data about energy balance (input and output) of rapeseed biofuel production, surveys in interview form were conducted in Poland and Netherlands. Questioners (Appendix 1 and Appendix 2) were developed for farmers to carry on Life Cycle Inventory (LCI) of rapeseed biofuel production from wheel-to-gate production. In order to support the surveys and also to fill the gap of missing data during the survey, literature where thoroughly assessed. Conversion of different inputs into the production of biofuel from rapeseed and output were used from

literature (Table 3). The interviews also helped in identifying the different rapeseed production stages at farm level.

The research was applied with second order EROEI, whereby direct inputs (energy and non-energy) and direct energy outputs were considered for both Poland and The Netherlands in order to reduce the discrepancy of using other inputs and outputs, which differ from place to place; and it is also considered as the most precise one (Mulder and Hagens, 2008). The direct energy inputs considered in the whole process of rapeseed biofuel production were energy for *cultivation* (ploughing and spraying), *transportation* (to and from market and agricultural field), rapeseed *conversion* into oil and Methyl Ester (RME). The indirect energies considered were energy allocation for *fertilization* (Nitrogen, Phosphorous, Potassium, and Manure), *crop protection* inputs (herbicides and pesticides), rapeseed oil cake (*meal*), *glycerine* and *straw.* Rapeseed Methyl Ester (*RME*) was considered to be the direct energy output (Figure 9).

### 2.3.2. Potential rapeseed area mapping

Suitability map for rain-fed oil crops with intermediate input was adopted from Global Agro-Ecological Zones (GAEZ) project, which is a collaborative work between Food and Agricultural Organization of the United Nations (FAO) and International Institute for Applied System Analysis (IIASA), for mapping of EROEI of rapeseed biofuel for the whole Europe assuming rapeseed and sunflowers are the most common oil crops. GAEZ suitability map is given in percentage of maximum attainable yield for a given area (Fischer et al., 2000). For estimation of maximum attainable yield, the Food and Agricultural Organizations (FAO) statistics of yield over the last twenty years (1961-2009) of all European countries is assessed. Accordingly, 5.2055 ton/ha (maximum over twenty years) of rapeseed was recorded in Luxembourg in 1980 production year, which was used for mapping of rapeseed yield over Europe assuming as maximum attained rapeseed yield. The GAEZ Model utilized a land resources inventory to assess feasible agricultural land-use options and to quantify expected production of cropping activities relevant in specific agroecological contexts, for specified management conditions and levels of inputs. The characterization of land resources includes components of climate, soils and landform, which are basic for the supply of water, energy, nutrients and physical support to plants. It was utilized in this research since the methodology and data they applied and used were deep and include all the necessary agro-climatic variables (climate and biophysical) (Fischer et al., 2000). The GAEZ results are based on a half-degree latitude/longitude world climate data set, 5-minute soils data derived from the digital version of the FAO Soil Map of the World, the 30 arc-seconds



Global Land Cover Characteristics Database, and a 30 arc-seconds digital elevation data set (Fischer *et al.*, 2002).

Figure 7. Flowchart of the study process

# 2.4. Life cycle inventory methodology and assumptions

The general framework for conducting Life Cycle Assessment (LCA) is found in ISO 14040 and 14044 standards (ISO, 1997), which were followed in this study with no focus on its impact assessment and interpretation. Life Cycle Inventory is the main focus for the estimation of the gross inputs and outputs of energy for the whole production system.

### 2.4.1. Goal of the study

The goal of the LCI analysis was comparative energy assessment study based on the inputs and output energies of winter rapeseed and RME production processes. The comparison was in terms of EROEI computation. RME and other biomass energy production are most often considering the ambitious energy independency of European countries. Less attention was given to look for efficient geographic production area based on feedstock crops production requirements and improving the production methodology including the system of production. The efficiency comparison was carried out with the intention of indicating the difference in energy benefit due to difference in agro-ecology and agricultural practices to the concerned bodies. It aimed at supporting the improvement of production system, decision and decision making concerning the different political support to producing countries and farmers at EU level. The result of this study addresses EU and member countries in the fore future production of rapeseed and rapeseed biodiesel for transport sector. The influences of different input levels and cultural method have been investigated.

#### 2.4.2. Scope of the study: functional unit and system boundaries

The function of the product biofuel from rapeseed is to serve as a fuel for combustion in motor vehicles. The function was quantified based on energy content (MJ) of biodiesel as a functional unit. The energy is per one hectare of rapeseed farm for reference flow.

Rapeseed methyl ester (RME) was explored for the Life Cycle Inventory (LCI), which uses rapeseed as feedstock with due emphases on material and energy flow through the whole production path. The crop cultivation, conversion to oil, and biodiesel production were considered for the analysis of energy efficiency. The primary concern of the LCI is to calculate all direct and indirect energy inputs and direct energy outputs for the calculation of EROEI. It helps to find out whether the different production systems affect the energy efficiency or not and indicates the causes and status of the efficiency. The different energy allocations were based on ISO LCA methodology and the interviews conducted with Polish and Dutch farmers. Where the interview is considered to be insufficient, literature for respective

countries and other similar LCA analyses were used. The inventory starts with the extraction of the feedstock (rapeseed) and ends with biofuel produced (RME).

The rapeseed biofuel production system consists of crop production, conversion to fuel and use of the fuel for combustion. Rapeseed production in Poland and Netherlands were considered as for LCI analysis in the study. Large and small scale farming and production were considered as spatial boundary. As a temporal boundary, cultivation and production season for 2009/10 were considered. Fuel energy flow for rapeseed production in case of cultivation (fertilizer, crop protection inputs) and conversion of rapeseed into biodiesel (with consideration of co-products in energy calculation) in large or small scale (start- and end-point boundaries) were considered as system boundary for LCI analysis.

The life cycle inventory (LCI) methodology followed was to determine the mass balance for the entire process and then from this to calculate the energy requirements for each process on the basis of MJ of biodiesel from one hectare of land as an output. The reference area for the production and use of rapeseed and RME were Poland and The Netherlands, whereas mapping of estimated EROEI was for Europe. Most of the data and the analysis were considered to be representative of the reference period of 2009/2010 and for these fact field visit and interviewing farmers were done in 2010 and literature used were in the near past.

### 2.4.3. Data collection methods

Data were collected by interviewing farmers to fill in questioners developed. Eight farmers in Poland and seven farmers in The Netherlands are interviewed for this purpose. Figure 8 shows relative locations of farmers interviewed for these purpose. As it can be seen on the figure the distribution of farmers happened to be all over the different suitability classes. This indicates that though the number of farmers is less their distribution is quite well distributed over different suitability classes. Farmers were contacted personally, through e-mail and telephone calls. The low number of farmers is due to difficulties in getting them to respond. Literature in Table 3 was used in order to understand the energy flow in each process activities and ways to convert the different material inputs into energy. They also help to establish bases for preparation of flow chart and baseline for energy balance.



Figure 8. Relative locations of farmers interviewed in the two case study countries 2.4.4. Computational model

Hereunder, different mathematical expressions for energy calculations are described. The energies calculated were: *fuel for cultivation* (CF), *fertilizer production energy* (NPK), *crop protection chemicals' production energies* (pesticides), *transportation energies*, *conversion energy* (co-product extraction and refining; and main product biofuel production), *by-products energy* (cake and straw) and *waste-product energy* (straw).

*Cultivation Energy:* this was from farmers' interviews result, which indicated the total diesel fuel in litre used per hectare during production season. Energy content of 35.9 MJ per litre of diesel fuel was used adopting from report of European Commission (The European Commission, 2005).

$$CE = 35.9 \times CF \dots 1^2$$

*Fertilizer Production:* the energy required for the production of the three major fertilizers (NPK) is calculated based on Lewis' (1997) energy allocation (Lewis, 1997) and formulated as:

$$FE = (65.3 \times N) + (8.6 \times P) + (6.4 \times K) \dots 2^3$$

Proceeding crop effect from straw (Braschkat, 2003) was assumed for the coming production year. Straw left over the land has a value of 32.5 kg of N/ha for the next year fertilizer application (Braschkat, 2003).

*Crop Protection:* energy required for production of insecticides, herbicides and fungicides was computed by allocating general energy requirement of 274.1 MJ/kg of the chemicals (Mortimer *et al.*, 2003) and computed as:

$$CPE = 274.1 (I + H + F) \dots 3^4$$

*Transportation Energy:* transportation was considered for round trip distance between the house and field; and rapeseed storage and market (most often to RME producing plants). Lewis (1997) used 32.8 l/100 km of diesel for transportation and the same was used for this study with energy content of 35.9 MJ per litre (The European Commission, 2005). Average distances from interview result were used.

$$TE = 2 \times 0.328 \times 35.9 \times (TF + TM) \dots 4^5$$

*Conversion energy*<sup>6</sup>: the energy need for extraction, refining and RME production are dependent on the yield of rapeseed and amount of biodiesel produced from it. Campbell and McCurdy (2008) stated the proportion of different conversion products and their energy is allocated accordingly (Campbell and McCurdy, 2008). Out of the rapeseed yield, 39.9% is converted to crude rapeseed oil. From this, 97.5% is converted to rapeseed oil (refined). Amount of biodiesel produced is to the proportion of 96.5% of refined rapeseed oil. 3.38 MJ/kg of biodiesel is adopted from the same citation and, thus, the energy for oil extraction is:

 $<sup>^{2}</sup>$  CE= Energy for cultivation (MJ/ha) and CF= Cultivation Fuel (l/ha)

<sup>&</sup>lt;sup>3</sup> FE=Fertilizer production energy (MJ/ha), N=Nitrogen fertilizer rate (kg/ha), P= phosphorus fertilizer rate (kg/ha) and K=potassium fertilizer rate (kg/ha)

<sup>&</sup>lt;sup>4</sup> CPE=energy required for production of crop protection chemicals (MJ/ha), I=insecticide rate (l/ha), H=herbicide rate (l/ha) and F=fungicide rate (l/ha). Note that density of the chemicals was estimated to that of water (1kg/l)

<sup>&</sup>lt;sup>5</sup> TE=energy required for transporting feedstock (MJ/ha), TF=average distance to farm (km) and TM=average distance to market (km). Note: the factor 2 is for round trip.

<sup>&</sup>lt;sup>6</sup> Note: numbers in the equations are rounded to two digits

$EE = 1268.88 \times Y$	5 <sup>7</sup>
$RE = 127.64 \times Y$	68
$BPE = 2890.65 \times Y$	7 <sup>9</sup>

Conversion energy is thus:



 $<sup>^7</sup>$  EE=input energy required for extraction of crude oil (MJ/ha) and Y=yield of rapeseed (ton/ha)

<sup>&</sup>lt;sup>8</sup> RE=input energy required for refining crude oil (MJ/ha) and Y= yield of rapeseed (ton/ha)

<sup>&</sup>lt;sup>9</sup> BPE=energy required for biofuel production (esterification) in MJ/ha and Y=yield of rapeseed (ton/ha)

Total energy invested is then the summation of all the energy required for cultivation, fertilizer production, chemical production, transportation and conversion energies.

$$TEI = CE + FE + CPE + TE + CoE \qquad \dots 9^{10}$$

*Main, by- and waste-product energies:* products which, are considered for energy calculation were straw, meal (cake), glycerine and RME. Campbell and McCurdy (2008), used economic allocation of 5.08 MJ/kg of biodiesel for rapeseed meal, primary energy credit of glycerine of 2.8 MJ/kg of biofuel or 13% of the total input energy required (TEI) and higher heating value (HHV) of RME to be 40.07 MJ/kg of biodiesel, which were used for output energy computations (Campbell and McCurdy, 2008). Braschkat (2003) indicated that the average value of preceding crop effect of straw, roots and empty pods to be 32.5 kg of N/ha (Braschkat, 2003) and energy required for production of this much fertilizer is considered as straw energy substitution (Lewis, 1997). Accordingly,

$EM = 1907.08 \times Y$	$ 10^{11}$
$EG = 0.13 \times TEI$	11 <sup>12</sup>
ES = 2122.25	12 <sup>13</sup>
$ERME = 15042.64 \times Y$	13 <sup>14</sup>

Thus, total energy return (direct and indirect) is the sum of energy from straw, meal, glycerine and RME.

$$TER = EM + EG + ES + ERME \quad \dots \quad 14^{15}$$

### 2.4.5. Energy efficiency computation

The research was applied with second order EROEI, whereby direct inputs (energy and non-energy) and direct energy outputs were considered for Poland and The Netherlands. EROEI is calculated as (Cleveland, 2008, Mulder and Hagens, 2008, Hall *et al.*, 2009):

<sup>&</sup>lt;sup>10</sup> TEI=total energy input (MJ/ha)

<sup>&</sup>lt;sup>11</sup> EM=energy allocated for rapeseed cake/meal (MJ/ha) and Y=yield of rapeseed (ton/ha). Numbers are rounded off to two digits

<sup>&</sup>lt;sup>12</sup> EG=energy allocated for glycerin (MJ/ha)

<sup>&</sup>lt;sup>13</sup> ES=energy allocated for straw (MJ/ha)

<sup>&</sup>lt;sup>14</sup> ERME=energy content of RME (MJ/ha)

<sup>&</sup>lt;sup>15</sup> TER=total energy return (MJ/ha)

$$EROEI = \frac{\text{Energy returned to society}}{\text{Energy required to get that energy}}$$
$$= \frac{TER}{TEI} \qquad \dots \ 15^{16}$$

### 2.5. Methodology used in mapping of EROEI

GAEZ suitability map is converted to yield map. Maximum attainable yield for rapeseed is given for rapeseed under different climate conditions in GAEZ model. For European condition temperate environments under rain-fed condition is used. Average of year 1960 – 1996 simulated maximum attainable crop yield ranges (t/ha) for intermediate level inputs in temperate environments under rain-fed condition for rapeseed crop is 2.3 to 3 (Fischer *et al.*, 2000). However, this yield is currently increased and FAO's statistics indicated 5.2055 t/ha recorded in 1980 in Luxembourg (FAO, 2010). This is used as maximum attainable yield under favourable condition and accordingly the yield levels were mapped. These yields then used in LCI EROEI model developed from the two countries, Poland and Netherlands, to get their respective EROEI under normal input condition. Averages of all inputs under the two countries were used for EROEI calculation over Europe. The mapped yield levels were used to show the converted energy from them. GAEZ's suitability map has got eight suitability classes as in Table 2 and Figure 10.

Class	Percent of Maximum attainable Yield	Suitability
0	Undefined	Undefined
1	85-100%	Very High
2	70-85%	High
3	55-70%	Good
4	40-55%	Medium
5	25-40%	Moderate
6	5-25%	Marginal
7	0-5%	Very Marginal
8	Not Suitable	Not Suitable
9	Water	Water

Table 2. Suitability classes given by Global Agro-Ecological Zones (GAEZ)

<sup>16</sup> EROEI=energy return on energy invested

References	(Lewis, 1997)	(Lewis, 1997)	(Lewis, 1997)	(Braschkat, 2003)		(Campbell and	McCurdy, 2008)	(Campbell and	McCurdy, 2008)	(Campbell and	McCurdy, 2008)	(World Petroleum	Council, 2009)	(Lewis, 1997)
Comment	It is input material and production energy is considered	It is input material and production energy is considered	It is input material and production energy is considered	By-product and its proceeding crop effect is considered	(32.5 kg N/ha replaced)	Process and energy required to extract crude oil from	rapeseed to get 1 kg of biodiesel is considered	Process and energy required to refine of crude oil to	get 1 kg of biodiesel is considered	Process and energy required to extract 1 kg of	biodiesel is considered	Process with litre of diesel per hectare		To and from the farm and market are considered
Energy Allocation factor	65.3 MJ/kg	8.6 MJ/kg	6.4 MJ/kg	2122.25 MJ/ha		3.38 MJ/kg of Biodiesel		0.34 MJ/kg of Biodiesel		7.7 MJ/kg of Biodiesel		35.6 MJ/L		32.8 L/100 km Diesel
Parameters	N	Ь	K	Straw		Oil Extraction		Oil Refining		RME	production	Cultivation		Transportation

Table 3. Literature used for the study on biodiesel production from oilseed rape


Figure 10. Suitability map according to Global Agro-Ecological Zones (GAEZ)

## 3. **RESULTS**

#### 3.1. Interview result

As stated in section 2.3 and 2.4, interviewing farmers helped to identify the different inputs and processes; and their quantity per hectare of rapeseed production in both countries. Table 4 and Figure 11 show the different inputs in the two countries. The inputs quantified and used in the LCI analysis for computation of energy input and output are diesel fuel used for cultivation of rapeseed (includes ploughing, weeding, spraying and harvesting) in litres, the three common fertilizers' (Nitrogen, Phosphorus and Potassium) rate in kg per hectare, crop protection chemicals (insecticides, herbicides and fungicides) in litres, yield of winter rapeseed in tonnes and distance of the farm from farmers' home (farm stead) and the market in km. All these were computed per hectares bases.

**Input Results from Interview** 



Figure 11. Different input results from interview and average over Europe



Figure 12. Yield of rapeseed based on the interview result

Investor	T L. 14		Poland		N	etherland	s	Europe
Inputs	Unit	Min	Aver	Max	Min	Aver	Max	Aver
Cultivation Fuel (1)	1	0.13	1.40	3	0.44	9.64	20	5.52
Nitrogen (kg)	kg	90	183.01	342.64	55	126	200	159.25
Phosphorus (kg)	kg	12	68.78	101.67	0	38.75	100	57.86
Potassium (kg)	kg	16	109.71	160	0	47.5	100	87.09
Insecticide (l)	1	0.3	1.1	2	0	0.23	0.75	0.61
Herbicide (1)	1	2	2.33	3	1.5	2.37	4	2.36
Fungicide (1)	1	0.8	1.43	2	0	0.62	1.5	0.97
Dist. to Field (km)	km	1	2.34	5	0.5	3.9	10	2.94
Dist. to Market (km)	km	10	83.75	300	2	52.8	100	71.84
Yield (ton)	ton	2.85	3.39	4	3	3.91	4.95	3.61

**Table 4.** Input and processes from interview and their quantities per hectare in both countries and Europe

# 3.2. Rapeseed farming system characteristics

# 3.2.1. Poland

According to the survey conducted, rapeseed farming in Poland is characterized by cultivation of the land with different inputs like fertilizers (NPK) and different crop protection chemicals. Farming activities from ploughing up to harvesting and

transportation of the yield to its storage area are using tractors and combine harvesters. Polish farmers plough and saw rapeseed once per growing season, 2 to 4 times fertilizer application and depending on the manifestation of herbs, pests and fungi they apply crop protection chemicals 3 to 4 times (0.3 to 3 l/ha). Cultivation of rapeseed is on land cover class of soils III to VI (good to poor). In addition to rapeseed, the most common crops grown by farmers are wheat, barley, maize and legume plants in rotation. Rapeseeds are grown in both summer and winter seasons. Average yield of rape seed is 3.39 tons per hectare for winter rapeseed production (Figure 12 and Table 4). Almost all farmers sell the yield produced to temporary storage companies, oil producing factories and biofuel producing refineries by themselves or through farmers' cooperation.

### 3.2.2. Netherlands

Due to high fertility of the soil (from previous years' organic and inorganic fertilizers application), Dutch rapeseed farmers, use less fertilizer input. Manure as organic fertilization is common practice, which has got its own contribution to energy efficiency computation. Like the Polish agricultural practice, farming activities are by using tractors and combine harvesters. Agro-chemicals (0 to 4 l/ha) are used as per the result from the interviews with farmers. Farmers commonly grow wheat, barley and maize in rotation. Production is both in winter and summer season, and the average yield for winter rapeseed is found to be 3.91 tons per hectare (Figure 12 and Table 4). Rapeseed produced was sold to domestic biodiesel factories or in some cases exported to Germany using tractors with trailer and tracks.

## **3.3.** Biofuel production feature

In both reference areas rapeseed is transported to oil mill and then pressed for extraction of rapeseed oil. Rapeseed meal (cake) which is the by-product of the extraction is mostly used for animal feed. Rapeseed methyl ester (RME) is produced from the extracted oil by means of transestrification process. Glycerine is the by-product of the process, which serves as a substitute for glycerine generated chemically. Electrical, fossil fuel and steam are the common energies used during the conversion of the feedstock.

# 3.4. Life Cycle Inventory

## 3.4.1. Unit processes

The processes and activities, which are identified for the calculation of EROEI through LCI of winter rapeseed biodiesel production, are (Figure 9):

- **Agriculture**: which is any activity for the production of the feedstock (oil seed rape) including cultivation (ploughing, spraying, harvesting), fertilizers, bio-fertilizers and agro-chemicals used.
- **Transport**: distance travelled to farm and market (any selling places)
- **Processing**: conversion of rapeseed to oil and eventually to rapeseed methyl ester (RME), which includes oil extraction, oil refining and biodiesel production

### 3.4.2. Results of calculation procedures

**Cultivation:** energy for cultivation was estimated from the response of farmers. The average litre of diesel per hectare for the whole cultivation operations was used in order to convert it into MJ energy. As a matter fact 37.9 MJ/l was used as conversion factor for it is stated as the energy content of diesel fuel (Energy System Research Unit, 2010). The average energy of cultivation in Poland is 50.15 and that of Netherlands is 346.25 MJ per hectare. Average energy for cultivation over Europe is 198.20 MJ/ha (Table 11).

**Fertilizers and Bio-fertilizer (Manure)**: Based on the survey, the average fertilizer application rates were determined and used for energy allocation in both countries. The energies required for the production of each fertilizer types (NPK) are 65.3, 8.6 and 6.4 MJ/kg of respective fertilizer (Lewis, 1997). Energy was allocated for manure used in Netherlands and Janulis (2003) allocated bio-fertilizer production energy to be 1993.5 MJ/ha, which is used in this study (Janulis, 2004). Average total energy required for production and replacement of different forms of fertilizers is 13244.21 and 10858.55 MJ/ha in Poland and Netherlands, respectively. Average energy required for fertilizers is 12451.12 over Europe (Table 5).

	nt		Ferti	lizer		_
Area	Amou	Nitrogen	Phosphorus	Potassium	Bio- fertilizer	Total
	Min	5877	103.2	102.4	0	6082.6
Poland	Aver	11950.56	591.50	702.15	0	13244.21
	Max	22374.56	874.39	1024	0	24272.95
	Min	3591.5	0	0	1993.5	5585
Netherlands	Aver	8227.8	333.25	304	1993.5	10858.55
	Max	13060	688	640	1993.5	16381.5
Europe	Aver	10399.41	497.59	557.37	996.75	12451.12

**Table 5.** Energy required (MJ/ha) for different rates of fertilizer for each countries and over Europe

**Agro-chemicals**: chemicals applied for crop protection as herbicides, insecticides, and fungicides forms. Volumes of the chemicals' concentration applied were calculated from farmers' response of individual crop protection chemicals in litre per hectare. Approximating the density of the chemicals equal to that of water and using 274.1 MJ energy of production per kg (Mortimer *et al.*, 2003) of the chemicals were used for energy allocation. Accordingly, 1334 and 887MJ/ha of energy is required to replace production energy of the chemicals in Poland and The Netherlands, respectively. Average energy required for chemical production over Europe is 1079 MJ/ha (Table 6).

**Table 6.** Energy required (MJ/ha) for different crop protection chemicals in case

 study areas and over Europe

Area	Amount		Chemical		Total
Alca	Amount	Insecticide	Herbicides	Fungicides	10141
	Min	82.23	548.2	219.28	849.71
Poland	Aver	301.51	639.57	392.88	1333.95
	Max	548.2	822.3	548.2	1918.7
	Min	0	411.15	0	411.15
Netherlands	Aver	65.10	650.99	171.31	887.40
	Max	205.57	1096.4	411.15	1713.12
Europe	Aver	166.42	646.09	266.27	1078.78

**Transport**: average round trip distance to the farm and market place from farm house was used for the calculation of energy required for transportation. Lewis (1997) used 32.8 l of diesel per 100 km (Lewis, 1997) and this is used to calculate the total litres of diesels used during transportation and multiplied by energy content (MJ) of diesel per litre (Energy System Research Unit, 2010). Poland and The Netherlands farming system contributes 2028 and 1335 MJ/ha of energy related to transport between farm and market, respectively. Average of Europe 1761 MJ/ha is required for transportation purpose (Table 7).

Area	Amount	Ref	erence	Total
Alta	Amount	To Field	To Market	- 10tai
	Min	23.55	235.50	259.05
Poland	Aver	55.20	1972.35	2027.54
	Max	117.75	7065.12	7182.87
	Min	11.78	47.10	58.88
Netherlands	Aver	91.85	1243.46	1335.31
	Max	235.50	2355.04	2590.54
Europe	Aver	69.29	1692.01	1761.30

Table 7. Energy required (MJ/ha) for transportation

**Conversion energy**: the energy required to convert rapeseed in to rapeseed oil (oil extraction), oil refining and biodiesel production (esterification) were calculated using mass balance of biodiesel produced from a given mass of rapeseed yield (Campbell and McCurdy, 2008). Accordingly, energy required for oil extraction of 3.38 MJ/kg of biodiesel, oil refining energy of 0.34 MJ/kg of biodiesel and esterification and production of biodiesel of 7.7 MJ/kg of biodiesel were adopted (Campbell and McCurdy, 2008) and used for calculation. As a result, total of 14523 and 16755.7 MJ/ha of energy were required in Poland and Netherlands, respectively for the conversion of feedstock in to final product, which is RME. The average energy required for conversion of rapeseed into RME over Europe is 15480 MJ/ha (Table 8).

				Parameter	S		
	Amount	Viald	Diadiasal	Oil	Oil	Biodiesel	Total
ea	Amount	(ton/ho)	(lrg/hg)	Extraction	Refining	Production	(MJ/ha)
Ar		(ton/na)	(kg/na)	(MJ/ha)	(MJ/ha)	(MJ/ha)	
	Min	2.85	1069.92	3616.32	363.77	8238.35	12218.44
lanc	Aver	3.39	1271.70	4298.34	432.38	9792.078	14522.8
$P_0$	Max	4	1501.64	5075.53	510.56	11562.6	17148.69
spui	Min	3	1126.23	3806.65	382.92	8671.95	12861.52
herla	Aver	3.91	1467.22	4959.22	498.86	11297.62	16755.7
Net	Max	4.95	1858.28	6280.97	631.81	14308.72	21221.5
Europe	Aver	3.61	1355.50	4581.57	460.87	10437.31	15479.75

Table 8. Energy required for the conversion the feedstock to final product

**Co-products and by-products**: Campbell and McCurdy (2008) used economic allocation of energy for rapeseed meal. The allocation was based on the economic value of animal feed replacing rapeseed meal and accordingly 5.08 MJ/kg biodiesel produced was used for ease of calculation (Campbell and McCurdy, 2008). Primary energy credit of 13% of total energy input for glycerine was used for the calculation and energy credit for straw was based on proceeding crop effect, which accounts for 32.5 kg of Nitrogen per hectare (Braschkat, 2003) and then the energy required to produce this amount of nitrogen fertilizer is allocated as straw energy credit (Lewis, 1997). Accordingly, total energy amount of 12636 and 13500 MJ/ha were contributed from the different co- and by-products from Poland and Netherlands production system, respectively. Average energy value of co- and by-product over Europe is found to be 13034 MJ/ha (Table 9).

Fable 9. Energy va	lue (MJ/ha)	of different co-	and by-products
--------------------	-------------	------------------	-----------------

Area	Amount		Parameters		Total
Alta	Allouin	Meal	Glycerine	Straw	- 10141
	Min	5435.17	2523.90	2122.25	10081.32
Poland	Aver	6460.23	4053.23	2122.25	12635.7
	Max	7628.31	6582.02	2122.25	16332.58
	Min	5721.24	2461.20	2122.25	10304.69
Netherlands	Aver	7453.50	3923.82	2122.25	13499.56
	Max	9440.04	5541.21	2122.25	17103.5
Europe	Aver	6885.92	4025.99	2122.25	13034.15

**RME (biodiesel):** higher heating value (HHV) in MJ of biodiesel is used per kg of biodiesel (Campbell and McCurdy, 2008), which is 40.07 MJ. Accordingly, Poland and Netherlands produce 50957 and 58792 MJ of RME, respectively. Average of Europe of 54315 MJ/ha of RME is produced (Table 10).

		Par	ameters
Area	Amount	Biodiesel	RME Energy
		(kg/ha)	(MJ/ha)
	Min	1069.92	42871.53
Poland	Aver	1271.70	50956.96
	Max	1501.64	60170.57
	Min	1126.23	45127.93
Netherlands	Aver	1467.22	58791.67
	Max	1858.28	74461.09
Europe	Aver	1355.50	54314.69

 Table 10. Energy value (MJ/ha) of Rapeseed Methyl Ester (RME)

### 3.4.3. Energy allocation

According to the above calculation procedures, energy contents of the materials, processes and energy (RME) produced results were drawn (Table 11). During extraction, 60.1% of rapeseed yield is converted to rapeseed meal the left (39.9%) is rapeseed oil. During refining process 97.5% of crude oil is refined and glycerine produced is 10% of the biodiesel produced (Campbell and McCurdy, 2008). Average total primary input energies were found to be 31179 and 30183 MJ/ha for Poland and The Netherlands, respectively. Average Europe input energy required for the production of biodiesel from the feedstock is found to be 30969 MJ/ha. The average total energies output from biofuel production system were 63593 and 72291 MJ/ha in Poland and The Netherlands, respectively. The average total energy output over Europe is 67349 MJ/ha (Table 11).

		Poland			Netherland	S	Europe
rarameters	Minimum	Average	Maximum	Minimum	Average	Maximum	Average
Seed (t/ha)	2.85	3.39	4	3	3.91	4.95	3.61
Energy Inputs (MJ/ha)	-						
Cultivation	4.79	50.15	107.7	15.80	346.25	718	198.20
Fertilizers	6082.6	13244.21	24272.95	3591.5	8865.05	14388	11454.37
Bio-fertilizer (Manure)	0	0	0	1993.5	1993.5	1993.5	996.75
Agro-chemicals	849.71	1333.95	1918.7	411.15	887.40	1713.13	1078.78
Transport	259.05	2027.54	7182.87	58.88	1335.31	2590.54	1761.30
Oil Extraction	3616.32	4298.34	5075.53	3806.65	4959.22	6280.97	4581.57
Oil Refining	363.77	432.38	510.56	382.92	498.86	631.81	460.87
<b>Biodiesel Production</b>	8238.35	9792.08	11562.6	8671.95	11297.62	14308.72	10437.31
Total Input Energy	19414.59	31178.65	50630.91	18932.34	30183.2	42624.67	30969.15
Energy Output (MJ/ha)	_		-				
Meal	5435.17	6460.23	7628.31	5721.24	7453.50	9440.04	6885.92
Glycerine	2523.90	4053.23	6582.02	2461.20	3923.82	5541.21	4025.99
Straw	2122.25	2122.25	2122.25	2122.25	2122.25	2122.25	2122.25
RME	42871.53	50956.96	60170.57	45127.93	58791.67	74461.09	54314.69
Total Output Energy	52952.85	63592.66	76503.16	55432.62	72291.23	91564.58	67348.84

Table 11. Input and output energies (MJ/ha) for different activities, processes and inputs

35

## 3.5. Energy Returned on Energy Invested

Energy returned on energy invested (EROEI) is calculated by dividing total primary output to input energies in MJ of the two countries. The total primary input energy is the sum of energy required for different activities and input materials and processes from the start of feedstock extraction up to production of the biodiesel in concern. Likewise, the total primary output energy is the sum of the energy allocated in MJ of all the co- and by-products and the biodiesel. Accordingly, the average EROEI of Poland and Netherlands are 2.04 and 2.4, respectively (Table 12). Note that all the energy inputs and outputs are considered per hectare of rapeseed production. The average EROEI value over Europe is found to be 2.18.

			Parameters	
Area	Amount	Total Input	Total Output	
Alta	Amount	Energies	Energies	<sup>17</sup> EROEI
		(MJ/ha)	(MJ/ha)	
	Min	19414.59	52952.85	2.73
Poland	Aver	31178.65	63592.66	2.04
	Max	50630.91	76503.16	1.51
	Min	18932.34	55432.62	2.93
Netherlands	Aver	30183.20	72291.23	2.40
	Max	42624.67	91564.58	2.15
Europe	Aver	30969.15	67348.84	2.18

Table 12. Primary Inputs and output energies with respective EROEI value

EROEI calculation methodology varies based on the consideration of the different co- and by-products of the whole process. EROEI interpretation needs careful consideration for minimum EROEI does not mean that minimum inputs were used but lower inputs likely result in higher EROEI result. This is exactly the situation in EROEI analysis in our case (Table 12). Table 13 and Figure 21 show that the resulting EROEI values for consideration of straw, meal and glycerine. Average first order EROEI of Poland and The Netherlands are 3.07 and 3.19, respectively. Average EROEI including straw are 1.7 and 2.02 for Poland and The Netherlands, respectively. Average EROEI including both straw and meal are 1.91 and 2.27 in Poland and The Netherlands, respectively. When all the co- and by-products included, average EROEI are 2.04 and 2.4 in Poland and The Netherlands,

<sup>&</sup>lt;sup>17</sup> EROEI values are for minimum, average and maximum inputs and outputs of the corresponding reference area. Therefore it is perfectly reasonable that minimal energy inputs result in higher or maximal EROEI.

respectively. The above four average EROEI values over Europe are 3.12, 1.82, 2.04 and 2.18, respectively (Table 13 and Figure 21).

### **3.6.** Energy efficiency gradient across Europe

## 3.6.1. Reclassified Global Agro-Ecological Zones map

Global Agro-Ecological Zones (GAEZ) data was reclassified and accordingly the original ten classes were reduced to eight classes merging unsuitable area, water bodies and areas with no data to be in one class called unsuitable class. Figure 13 and Table 14 shows the reclassified suitability map and proportion of their area coverage.

## 3.6.2. Map of rapeseed yield

Based on reclassified suitability map result of GAEZ and maximum yield attained in 1980 of Luxembourg, map of yield of rapeseed across Europe was produced in ArcGIS interface. Table 14 indicates area under each suitability class and their corresponding yield in ton/ha. Figure 14 is map result of yield of rapeseed over Europe based on the suitability data used.

## 3.6.3. Map of Energy Return On Energy Invested

The EROEI values of each suitability class were calculated based on the method described in section 2.5 and the following results were found. The yields in section 4.2.1 were used in the model developed from the two countries LCI analysis for computation of energy allocation and EROEI. As a result EROEI ranges map in Figure 15 was produced. Areas under EROEI value less than 1.28 were classified in two one in order to depict inefficient areas in terms of EROEI. The reclassified EROEI map is shown in Figure 16.

### 3.6.4. Country based yield and EROEI from EROEI gradient map

Country base average ranges of yield and EROEI were analysed. As a result, the average maximum and minimum yields and EROEI for each country over suitable areas, which are capable of growing rapeseed, are indicated in Appendix 4. This result helped to indicate the variation in yield and EROEI values because of the embedded agro-physical differences between each countries affecting yield and in turn EROEI values.

EDOEL I and		Poland			Netherlands		Europe
ENUEL LEVEL	Minimum	Average	Maximum	Minimum	Average	Maximum	Average
First Order EROEI			-			-	
Input Energies (MJ/ha)	12482.28	16600.49	24439.26	12936.19	18437.25	24530.05	17439.25
Output Energies (MJ/ha)	42871.53	50956.96	60170.57	45127.93	58791.67	74461.09	54314.69
EREOI	3.44	3.07	2.46	3.49	3.19	3.04	3.12
<b>EROEI</b> with straw			-				
Input Energies (MJ/ha)	19414.59	31178.65	50630.91	18932.34	30183.2	42624.67	30969.15
Output Energies (MJ/ha)	44993.78	53079.21	62292.82	47250.18	60913.92	76583.34	56436.94
EREOI	2.32	1.70	1.23	2.50	2.02	1.80	1.82
EROEI with straw and M	leal		-			-	
Input Energies (MJ/ha)	19414.59	31178.65	50630.91	18932.34	30183.2	42624.67	30969.15
Output Energies (MJ/ha)	50428.96	59539.43	69921.14	52971.42	68367.41	86023.37	63322.85
EREOI	2.60	1.91	1.38	2.80	2.27	2.02	2.04
EROEI with straw, meal a	and glycerine		-			-	
Input Energies (MJ/ha)	19414.59	31178.65	50630.91	18932.34	30183.2	42624.67	30969.15
Output Energies (MJ/ha)	52952.86	63592.66	76503.16	55432.62	72291.23	91564.58	67348.84
EREOI	2.73	2.04	1.51	2.93	2.40	2.15	2.18

Table 13. Different EROEI values under different considerations

38



Figure 13. Reclassified Global Agro-Ecological Zoning (GAEZ) data

Percent Potential	Yield (ton/ha)	Switchility	Area (ha)	EDOEI
Yield	Range	Sunability	Alea (lla)	EKUEI
85-100%	4.42-5.2	Very High	28200000	2.32-2.48
70-85%	3.64-4.42	High	36350000	2.14-2.32
55-70%	2.86-3.64	Good	65920000	1.91-2.14
40-55%	2.08-2.86	Medium	102670000	1.53-1.91
25-40%	1.3-2.08	Moderate	109820000	1.24-1.53
5-25%	0.26-1.3	Marginal	154950000	0.51-1.24
0-5%	0-0.26	Very Marginal	69420000	0-0.51
Not Suitable	0	Not Suitable	257460000	0

**Table 14**. Area of different suitability classes and their corresponding yield and EROEI range



Figure 14. Map of corresponding yield value of GAEZ suitability classes



Figure 15. Map of EROEI value for corresponding yield values of GAEZ suitability classes



**Figure 16.** Reclassified EROEI map indicating areas with EROEI value less than 1.28

### 4. DISCUSSION

#### 4.1. Rapeseed biofuel production system and EROEI

For the calculation of EROEI, which is used in the study as energy efficiency indicator, primary energy inputs and outputs were very important. The more the energy input, the less is EROEI value and the more energy output, the more is EROEI value and vice versa. Primary energy input is dependent on energy related to both material and process inputs. As the contribution of these processes and materials increases, the energy input also increases. Energy inputs related to materials are those for fertilizer and agro-chemicals, which improve the yield of the feedstock crop. Processes, which affect the energy input, were energy for cultivation, transport and biodiesel production. Nitrogen, phosphorus and potassium were the three commercial fertilizers, which increase the fertilizer application. Straw left on the field affects the amount of fertilizer application for the preceding year. Energies for biodiesel production were used for oil extraction, refining and esterification (biodiesel production). The amount of oil, glycerol and RME were directly related to the yield of rapeseed. The meal, which serve as animal feed, straw left over, glycerine and RME were energy contributors for output energy (Figure 17).



Figure 17. Casual loop diagram of EROEI and rapeseed biodiesel production system

### 4.2. Impacts of different inputs on energy efficiency

Different inputs, activities and processes did have their own impact on LCA analysis result. Energy efficiency depends on "climate condition and agro- and processing technology used" for the production of the biofuel (Janulis, 2004). The share of their impact on production of rapeseed methyl ester (RME) and overall energy efficiency in terms of EROEI is discussed hereunder for major inputs and processes. The inputs considered are yield and fertilizer, where as the processes focused are oil extraction and biodiesel production. These are selected for they have are the major contributors compared to the others as shown in Figure 18 and Table 15.



Average Energy Input (MJ/ha)

Figure 18. Energy allocation of different input components

### 4.2.1. Yield

Since yield is one of the variables for calculation of EROEI, every unit change in yield changes the EROEI value. Keeping all the other inputs constant (average of Poland and Netherlands), different yield values had got relation with EROEI as shown in Table 22 and Figure 19. Lewis (1997) indicated that energy inputs and yield per hectare depend on the different cultural practices and agro-climatic conditions (Lewis, 1997). This is clearly shown in the two case study countries, which have different agricultural practices and agro-ecologies as indicated from the interview results. Hou *et al* (2008) described soybean yield as a key factor in lifecycle analysis as it affects the energy use (Huo *et al.*, 2008), which supports the finding. The yield of the feedstock makes some production chains more desirable

than others (Cherubini et al., 2009). Most of the conversion processes and their output from rapeseed under consideration depend on the amount of feedstock from a given area. Accordingly, the energy efficiency (EROEI) as dependant on yield is shown in Table 16 and Figure 20. Yield of FAO average over twenty years, average over suitable area of yield map and yield from case study countries were compared for most European countries. Yield result from interview is greater than twenty years FAO yield average and average yield over different yield areas in both Poland and The Netherlands. This does not mean the yield reach the attainable potential because of different reasons (Grzebisz et al., 2010). Latvia and Lithuania produce higher yield over Europe based on yield mapping. Netherlands' production return is high as compared to Poland in all sources (Figure 19). Variation in yield from place to place has got implication in the final return from the energy production. Areas producing high yield, due to suitable area in terms of agro-ecological conditions, yield boosting mechanisms, and other embedded factors, have got higher EROEI value in most cases. Countries having higher FAO yield statistics yield as compared to yield estimated from suitability map are adding additional cost for different inputs to increase the yield beyond the natural capacity of the area. There are still countries, which can produce more than the actual FAO statistics data. This might be because they are not producing at maximum potential of the suitable area. Figure 19 shows yield variation between the actual FAO statistics yield and yield estimation from suitability indexes.



Figure 19. Yield comparison between countries from different sources

EROEI value as dependent on yield of rapeseed based on the model developed from the two countries is given by an equation:

 $EROEI = -0.0039Y^{6} + 0.0669Y^{5} - 0.4449Y^{4} + 1.4514Y^{3} - 2.4615Y^{2} + 2.535Y + 0.0023$ Where Y is yield of rapeseed in ton/ha

### 4.2.2. Fertilizers

The fertilizers considered for the energy allocation are artificial fertilizers for the three basic elements (NPK) and bio-fertilizer (manure application, which is common in The Netherlands). The difference in rate and type of fertilizers in the two countries caused different energy requirement for the production and replacement of bio-fertilizer. Out of the three commercial fertilizers, nitrogen fertilizer caused the higher energy requirement for production as its production energy per kg is higher (65.3 MJ). It is reported that 12100, 400 and 300 MJ/ha of energy introduced in winter rapeseed production from nitrogen, phosphorus and potassium fertilizers, respectively (Lewis, 1997). The more the application rate, the more energy is expected for the production (Figure 18), which accordingly the energy for fertilizer production is higher in Poland (13244 MJ) than The Netherlands (10859 MJ). Table 6 shows the detail energy requirement in MJ for individual fertilizer type and over all energy. Artificial fertilizers contributed 42, 29 and 37% of input energy in Poland, The Netherlands and across Europe on average, respectively. Nitrogen fertilizer contributes above 90% of energy required for production of artificial fertilizers in Poland, The Netherlands and Europe. The less artificial application in The Netherlands is due to use of bio-fertilizer and precision farming for more yield earnings as compared to Poland. This implies that application of optimum rate of fertilizer and use of other alternative fertilizers help in improving the energy efficiency through decreasing the overall input energy.

#### 4.2.3. Oil extraction

Oil extraction is the third most energy requiring process next to fertilizer and biodiesel production (esterfication) (Figure 18 and Table 8). Energy required for oil extraction is higher in The Netherlands (4959 MJ) than in Poland (4356 MJ). This is explained by the higher yield to be converted into oil in The Netherlands per hectare of rapeseed (Campbell and McCurdy, 2008). This indicates that some processes (oil extraction) are cheaper in terms of energy cost from place to place, though they are driven by yield of the feedstock. Oil extraction energy shares 14, 16 and 15% of total input energy in Poland, The Netherlands and Europe, respectively. State of the art of biofuel production plants determines improvement in the energy required for oil extraction for a given yield of feedstock.

### 4.2.4. Biodiesel production

It is the second more energy requiring process in biodiesel production from rapeseed (Figure 18 and Table 8). This is the process of converting the oil to Methyl Ester by adding alcohol or ester to the oil. Like oil extraction, energy required for esterification is higher in The Netherlands (11298 MJ/ha) than in Poland (9792

MJ/ha). Both oil extraction and biodiesel production are function of yield of the feedstock (Campbell and McCurdy, 2008) which, as a result the energy required in The Netherlands' production system is higher for these two processes. Biodiesel production energy (esterification) shared 31, 37 and 34% of total input production energy in Poland, The Netherlands and Europe, respectively. Total RME produced per hectare over Europe is 1355.5 kg, which is very much close 1406 kg/ha of Halleux *et al.* (2008) review.



Figure 20. Relationship of yield and EROEI

#### 4.2.5. Other inputs and processes

Energy for cultivation in Poland (50 MJ/ha) is much less than that of The Netherlands' (346 MJ/ha). Polish farmers use 64 litres of diesel fuels on average over 62 ha average farm area, where as The Dutch farmers use about 104 litres of diesel fuel for cultivation of an average area of 50 ha. Rapeseed cultivation process fuel consumption is estimated to be 70 litres per one hectare (Su and Lee, 2008). This in turn increased the average diesel fuel per unit area of land in The Netherlands' rapeseed farming system. The interview result showed that only Dutch farmers are using bio-fertilizer (manure), which of course has got impact on the amount of artificial fertilizers used in the preceding years. Bio-fertilizer has got around 6.6% energy contributions, which if it would have been used in Polish farming system, about 4.9 litres of agrochemicals are applied on average and 3.2 litres in The Netherlands per hectare. The comparative difference in the amount of

agro-chemicals applied on unit area of land made the energy used for the production of chemicals to be higher in Poland system. The average energy requirement for agro-chemicals in Poland (1334 MJ/ha) and The Netherlands (887 MJ/ha) are more than 600 MJ/ha as reported by Lewis (1997). This variation is due to energy allocation methodology. As an example, range of 316 to 1002 MJ/ha of energy is allocated in Batchelor *et al.* (1995). For the only two considerations of distances, distance to the farm and to market place, energy expenditure in Poland (2028 MJ/ha) is higher than that of The Netherlands (1761 MJ/ha). This is because of the longer distances covered to the farm field and market. Since the refining efficiency of most refining plants is high (close to 98%) and less energy required (Campbell and McCurdy, 2008) (0.34 MJ/kg of crude oil), the energy required for refining is generally less. In this case, The Netherlands (499 MJ/ha) production system required higher energy as compared to the Polish system (432 MJ/ha).

### 4.3. Impacts of different products on energy efficiency

Contributions of the different by- (Meal and Glycerine) and waste-products (straw) on the overall energy efficiency of rapeseed biodiesel production are discussed hereunder. Table 23 shows the different products and their energy contribution (MJ/ha) to the overall system. All the energy contribution from these by- and waste-products imply that the more their contribution the more is the energy efficiency of biodiesel production system (Table 17).

#### 4.3.1. Meal

This is the major contributor to the energy from by- and waste products constituting 6460 MJ in Poland and 7454 MJ in The Netherlands. Since the energy allocation was based on the yield of the feedstock (rapeseed) and it is higher in The Netherlands, the energy saving from meal in the later case is high. It is 50 and 55% energy contribution from the by- and waste products in Poland and The Netherlands, respectively. In general, it has more than 50 percent energy cost, which is worth considering in energy efficiency analysis. Average over Europe, it contributed 6886 MJ of energy per hectare to the output energy, which worth 10% of the total output energy. Halleux *et al.*, (2008) reported 2224 kg/ha of meal, which in this research found to be 2170 kg/ha (average) over Europe. Energy contributed by rapeseed meal is by far less than what is reported by Bachelor *et al.* (1995), which is 11004 to 45507 MJ/ha. Meal energy result is still more than Lewis (1997) finding, which is 3700 MJ/ha. The differences in energy content of rapeseed meal are due energy allocation methods in LCI analysis.

### 4.3.2. Glycerine

Glycerine is the second energy compensating product with 33 and 28% energy contribution in Poland and The Netherlands, respectively. Unlike energy from meal, the energy contribution from glycerine in Poland (4053 MJ) is higher than that of The Netherlands (3923 MJ). One third of the energy contribution, from by- and waste products goes to glycerine's in general. Average energy contribution of glycerine over Europe is 4026 MJ/ha. Energy content result of glycerine is closer to 1679 to 3361 MJ/ha report of Batchelor *et al.* (1995).

#### 4.3.3. Straw

The lowest energy contribution from by- and waste products, though it is not the least if it is used as energy source for conversion process, is from straw left on the field after harvest. Both countries have same energy contribution from straw as the energy allocation was not on the amount of straw but preceding crop effect. Energy for both countries is 2122 MJ/ha, which is the same over Europe too. Energies contributed from straw are 3.34, 2.94 and 3.15% of total output MJ/ha of energy in Poland, The Netherlands and Europe. Contribution of rapeseed straw is not considered in most LCA studies (Bernesson *et al.*, 2003, Campbell and McCurdy, 2008). Having such contributions in this energy analysis, including straw is important in energy efficiency study.

#### 4.4. Energy efficiency indication using EROEI

The energy efficiency indicator used is EROEI and it is different in both countries. Since it is computed from energy inputs and outputs from different processes, inputs and outputs, it is important to show the production efficiency of biofuels from different feedstock (rapeseed in this case) in terms of MJ energy per hectare. Average EROEI values are 2.04 and 2.40 (including all the by- and waste-products) in Poland and The Netherlands, respectively. This indicates that production system of The Netherlands is more efficient than that of Poland under the stated and used system boundary and methodologies. In order to produce 2.04 MJ of RME, Polish system consumes 1 MJ of energy in different forms; and The Netherlands' utilize 1 MJ to produce 2.4 MJ of energy. Both countries are producing rapeseed biofuel in sustainable way as their EROEI value in different levels is greater than one (The Offshore Valuation Group, 2010). EROEI at Europe level is 2.18, still more than one. Since the energy output is greater than the total energy input in all the cases, rapeseed biofuel production has a positive energy benefit (Su and Lee, 2008). Worth mentioning is the effect of different by- and waste-products on EROEI values. Batchelor et al. (1995) have reported EROEI ranges considering the different byand waste-products. Their result indicates that EROEI range of 2.22 to 9.18 including RME, rapeseed, glycerine and straw for different scenarios. For the same consideration of the four products, average EROEI values of 2.04, 2.4 and 2.18 are found in this study for Poland, The Netherlands and Europe, respectively (Figure 21).



**EROEI** Level Comparison

## 4.5. Energy efficiency gradient over Europe

Less is done on mapping of EROEI as energy efficiency indicator in the past. This made supporting and comparing the discussion of the result found in this research with different literature difficult. United States ethanol EROEI is mapped ranging from 0 to 1.39 with specific EROEI value for each state (Hall *et al.*, 2006). The maximum EROEI value across Europe is found to be 2.52 at maximum attainable yield and the minimum of 0 where rapeseed growing is unsuitable. Most European countries fall under the EROEI value of 1.24 to 2.32. Table 18 shows the area covered and percentage of particular EROEI value range. More than 26% of the total areas in Europe are producing rapeseed biofuel with no any benefit and even under energy loss.

### 4.6. Regional and country based EROEI

Europe was divided into four regions as shown in Figure 25 for the purpose of EROEI gradient analysis. Accordingly, West and East Europe have got higher EROEI value areas compared to North and South Europe. North Europe has got vast

Figure 21. EROEI levels comparison

area with zero EROEI value which is typically due to unsuitability of the region for rapeseed production. Majority of West Europe have got EROEI value less than 1.66. West and East Europe are the most contributors of energy positive rapeseed production as their EROEI coverage above 1.22 adds to larger areas of the whole Europe. Improving the production efficiency of Western and East Europe will increase their share to their contribution towards much more higher EROEI areas.

Country bases EROEI analysis indicated in Appendix 3. According to the analysis, not all countries have suitable area for the production of rapeseed, which as a result affect the EROEI value as it depends on yield of the feedstock crop. Some illustrative examples of EROEI values and their area proportion are shown in Figure 22. The two countries, which were used as case study areas have difference in EROEI output. Poland has got many areas with higher EROEI as compared to the Netherlands. Some countries, like Germany, are the major contributors to the European higher EROEI rapeseed biofuel production, which is related to the difference in their suitability areas controlled by the climatic and agro-physical conditions for the feedstock crop production.

### 4.7. Implication of EROEI value from different yield sources

Different European countries are yielding different EROEI value based on their corresponding yield. EROEI values for a given country depend on the assumed yield values, which depends on the sources and analysis of yields. For the two case study countries, Poland and The Netherlands, EROEI based on average yield from interviews is higher than both the FAO twenty years average yield and yield estimated from suitability analysis. There are three scenarios with respect to variation in EROEI due to different rapeseed yield sources (FAO statistics and from suitability analysis) over a given country (Table 19):

- Scenario A. EREOI value based on FAO yield is equal to EROEI based on estimated yield from suitability analysis
- Scenario B. EROEI value based on FAO yield is greater than EROEI based on estimated yield from suitability analysis
- Scenario C. EROEI value based on FAO yield is less than EROEI based on estimated yield from suitability analysis

Countries under scenario A seem to produce at maximum potential of the suitable area for rapeseed production at input rate assumed to be the same over Europe. Counties under scenario B are introducing inputs (technological or yield enhancing inputs) greater than the constant input for rapeseed production considered in the model. Countries under scenario C are producing under their productivity potential. They have got area to produce much yield with same input. They might be producing rapeseed on less suitable areas.

Any technology and input for enhancing the production of the feedstock crop is at the expense of energy. As a result almost half of the European countries are under this category. The other aspect related to this is, these countries might be boosting their technology and input on less suitable areas, though the suitability map produced for each country or overall Europe is general. Countries under scenario B are those who are producing rapeseed biodiesel at higher energy cost in order to increase the yield of the feedstock. Especially Belgium, Ireland, Luxembourg, Netherlands and United Kingdom are increasing EROEI (Figure 23 and Figure 24) of rapeseed biodiesel by much more energy investment in increasing yield of rapeseed. Though the suitability map is generalized over all land use in the countries, consideration of whether suitable areas are used for feedstock production, which makes less yield enhancing input, is important.



Figure 22. EROEI map results of some European countries



Figure 23. EROEI values from different rapeseed yields in European countries



Figure 24. EROEI differences from FAO and Suitability yields for countries under scenario B



Figure 25. Regional EROEI map of Europe

input energy
of each
contribution
Percent
Table 15.

	Polanc	1	Netherlar	lds	Europe	
Innit	Average Input		Average Input		Average Input	
mdu	Energy	Percent	Energy	Percent	Energy	Percent
	(MJ/ha)		(MJ/ha)		(MJ/ha)	
Cultivation	50.15	0.16	346.25	1.15	198.20	0.64
Fertilizer	13244.21	42.48	8865.05	29.37	11454.37	36.99
Bio-fertilizer	0	0	1993.50	6.61	996.75	3.22
Agro-Chemicals	1333.95	4.28	887.40	2.94	1078.78	3.48
Transport	2027.54	6.50	1335.31	4.42	1761.30	5.69
Oil Extraction	4298.34	13.79	4959.22	16.43	4581.57	14.79
Oil Refining Biodiesel	432.38	1.39	498.86	1.65	460.87	1.49
Production	9792.08	31.41	11297.62	37.43	10437.31	33.70
Total	31178.65	100	30183.20	100	30969.15	100

Table 16. Yield and EROEI relation

Yield <sup>18</sup> (ton/ha)	EROEI	Input Energy	Output Energy
5.2055	2.51992186	37806.27	95268.84
4.424675	2.36801761	34458.74	81598.90
3.64385	2.1834239	31111.21	67928.95
2.863025	1.95431641	27763.67	54259.01
2.0822	1.66238618	24416.14	40589.06
1.301375	1.27768803	21068.61	26919.11
0.26075	0.52391715	16607.27	8700.84
0	0	13728.1	0

Table 17. Energy contribution of different products per hectare of rapeseed produced

	Pola	pu	Netherl	ands	Euro	be
Products	Energy (MJ/ha)	Percent	Energy (MJ/ha)	Percent	Energy (MJ/ha)	Percent
Meal	6460.23	10.16	7453.50	10.310	6885.92	10.22
Glycerine	4053.23	6.37	3923.82	5.43	4025.99	5.98
Straw	2122.25	3.34	2122.25	2.94	2122.25	3.15
RME	50956.96	80.13	58791.67	81.33	54314.69	80.65
Total	63592.66	100	72291.23	100	67348.84	100

 $^{18}$  The yield value used, in this case, is from suitability and yield estimation mapping.

EROEI Range	Area under each EROEI class (km <sup>2</sup> )	Percent
2.37-2.52	282000	3.42
2.18-2.37	363500	4.41
1.95-2.18	659200	7.99
1.66-1.95	1026700	12.45
1.28-1.66	1098200	13.32
0.52-1.28	1549500	18.79
0-0.52	694200	8.42
0	2574600	31.22
Total	8247900	100

Table 18. Area and percentage of area with particular EROEI value ranges

Table 19. European countries under the three scenarios

Scenario A	Scenario B	Scenario C
Czech Republic	Austria	Bulgaria
Denmark	Belgium	Cyprus
Estonia	France	Hungary
Finland	Germany	Latvia
Poland	Greece	Lithuania
Spain	Ireland	Malta
	Italy	Portugal
	Luxembourg	Romania
	Netherlands	
	Slovakia	
	Slovenia	
	Sweden	
	Switzerland	
	United Kingdom	

## 5. CONCLUSION AND RECOMMENDATION

Based on the method employed and findings of the research the following conclusions are drawn:

- Improving the energy efficiency of rapeseed biodiesel is always crucial in contributing to the reduction of GHG emission. There is, still, potential of increasing the productivity of majority of European countries as their agro-physical conditions are suitable for the production of rapeseed production.
- It has been depicted that different inputs and processes have different impact on overall energy efficiency. The study concluded that fertilizer input, especially nitrogen fertilizer, has got great impact on reducing efficiency of energy production from rapeseed. As a result using less fertilizer consuming technique of production will benefit energy production for the feedstock used.
- Since the produced amount of the biofuel depends on the yield of the feedstock, based on the method adopted for this research, using high yield variety with same input will improve the EROEI of rapeseed biofuel. In addition to variety of rapeseed, agro-ecologies (soil and climatic conditions) that increase the yield of rapeseed should be sorted out to benefit from the system.
- The most energy consuming process of production of biofuel from rapeseed is biofuel production. The use of different alternative energies and bi- and waste products as energy sources will benefit in saving the energy consumption. Such products can be used as energy source in biofuel production process (esterification) in particular and whole process in many ways.
- Due to the overall interaction of inputs, agro-climatic conditions and production techniques, biofuel production from rapeseed is more effective in The Netherlands (higher by 24.4%) than that of Poland, which might be justified by its more precision farming, alternative and less fertilizer usage during cultivation.
- EROEI value varies spatially and consideration should always be there where and why to produce rapeseed in a particular area. Most European countries are producing rapeseed with less energy benefit. Such countries

should look for suitable area of production, if in case they are not producing rapeseed on such areas.

The following limitations are found to be problems in finding more refined findings and corresponding recommendations for further research are described:

- Most LCA analysis were relaying on literature from long. The same method was used for energy allocation for biofuel production processes and by- and waste products in this study. This is due to logistic problems and limited time and resources. The dependence on literature is not reliable. We suspect methodologies used in literature are not always clear. Time factor is also always be there as error propagator. Effort was made in this research not to use literature for different inputs and process for cultivation of rapeseed and using the same methodology for biofuel production (conversion of the feedstock to fuel) is always recommended for more indicative result.
- Getting information from refining plants was not as easy as expected and proposed, which might be due to 'criticizing' nature of LCA. As a result of fact, the intended interview with refineries did not work in most of the cases. Studies about causes of such confidentiality are so crucial and if, in case, the above hypothesis is true, using LCA for problem identification and solution seeking is strongly recommended. Owners of refineries should be open enough in such a way that weak points of their system be identified and alternative options are drawn. In addition to that, their production system should serve the whole community and the environment.
- The causes of EROEI difference over space should be well studied. The EROEI gradient produced here is based on Global Agro-Ecological Zones (GAEZ) methods and data of ten years back. Suitability criteria of rapeseed production could not be easily found to the scope of this research. Hence, suitability study and yield estimations under different suitability status and input levels are of the most importance.
- Mapping of the different inputs and process of biofuel production is important for the availability of information. Using other feedstock crops other than rapeseed and comparing among each other will also give a clear picture where, why and what to grow for biofuel production.
#### 6. **REFERENCES**

- AJANOVIC, A. 2010. Biofuels versus food production: Does biofuels production increase food prices? *Energy*, xxx, 1-7.
- ARVIDSSON, R., PERSSON, S., FROLING, M. & SVANSTROM, M. 2011. Life cycle assessment of hydrotreated vegetable oil from rape, oil palm and Jatropha. *Journal of Cleaner Production*, 19, 129–137.
- BAKA, J. & ROLAND-HOLST, D. 2009. Food or fuel? What European farmers can contribute to Europe's transport energy requirements and the Doha Round. *Energy Policy*, 37, 2505–2513.
- BATCHELOR, S. E., BOOTH, E. J. & WALKER, K. C. 1995. Energy analysis of rape methyl ester (RME) production from winter oilseed rape. *Industrial Crops and Products*, 4, 193-202.
- BERNESSON, S., NILSSON, D. & HANSSON, P. A. 2003. A limited LCA comparing large- and small-scale production of rape methyl ester (RME) under Swedish conditions. *Biomass and Bioenergy*, 26, 545 – 559.
- BOMBA, C., MCCORMICKB, K., DEURWAARDERC, E. & KÅBERGER, T. 2007. Biofuels for transport in Europe: Lessons from Germany and the UK. *Energy Policy*, 35, 2256–2267.
- BÖRJESSON, P. 2008. Good or bad bioethanol from a greenhouse gas perspective What determines this? *Applied Energy*, 86 (2009), 589–594.
- BÖRJESSON, P. & TUFVESSON, L. M. 2009. Agricultural crop-based biofuels resource efficiency and environmental performance including direct land use changes. *Journal of Cleaner Production*, xxx, 1–13.
- BRASCHKAT, J. 2003. Final Report. *Life Cycle Assessment of Biodiesel: Update and New Aspects.* Institute for Energy and Environmental Research (IFEU) Heidelberg.
- BRECHA, J. R. 2008. Emission scenarios in the face of fossil-fuel peaking. *Energy Policy*, 36, 3492–3504.
- BUREAU, J.-C., DISDIER, A.-C., GAUROY, C. & TRE'GUER, D. 2009. A quantitative assessment of the determinants of the net energy valuen of biofuels. *Energy Policy*, 38, 2282–2290.
- CAMPBELL, A. & MCCURDY, M. 2008. Primary Energy and Greenhouse Gas Emissions from Biodiesel Made from Southland Rapeseed. *CRL Energy Limited Report*. CRL Energy Limited.
- CHERUBINI, F., BIRDA, N. D., COWIE, A., JUNGMEIERA, G., SCHLAMADINGER, B. & WOESS-GALLASCHA, S. 2009. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling*, 53, 434–447.
- CHERUBINI, F. & STRØMMAN, A. H. 2010. Life Cycle Assessment of bioenergy systems: State of the art and future challenges. *Bioresource Technology*, 1-41.
- CHIARAMONTI, D. & RECCHIA, L. 2010. Is life cycle assessment (LCA) a suitable method for quantitative CO2 saving estimations? the impact of

field input on the LCA results for a pure vegetable oil chain. *biomass and bioenergy*, 34, 787–797.

- CIA. 2010a. The World Factbook. *Netherlands* [Online]. Available: https://www.cia.gov/library/publications/the-world-factbook/geos/nl.html.
- CIA. 2010b. The World Factbook. *Poland* [Online]. Available: https://www.cia.gov/library/publications/the-world-factbook/geos/pl.html.
- CLARK, G. & LEEUW, B. D. 1999. How to Improve Adoption of LCA. International Journal of Life Cycle Assessment 4, 184 - 187.
- CLEVELAND, C. J. 2008. Energy return on investment (EROI). *Encyclopedia of the Earth*.
- CLEVELAND, C. J., COSTANZA, R., HALL, C. A. S. & KAUFMANN, R. 1984. Energy and the U.S. Economy: A Biophysical Perspective. *Science, New Series*, 225, 890-897.
- CRUTZEN, P. J., MOSIER, A. R., SMITH, K. A. & WINIWARTER, W. 2008. N<sub>2</sub>O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry and Physics*, 8, 389–395.
- DAVIS, S. C., ANDERSON-TEIXEIRA, K. J. & DELUCIA, E. H. 2009. Life-cycle analysis and the ecology of biofuels. *Trends in Plant Science*, 14.
- DEMIRBAS, A. 2008. Biofuels sources, biofuel policy, biofuel economy and global biofuel projections. *Energy Conversion and Management*, 49, 2106–2116.
- ENERGY SYSTEM RESEARCH UNIT. 2010. *Biodiesel Production* [Online]. University of Strathclyde. Available: <u>http://www.esru.strath.ac.uk/EandE/Web\_sites/02-</u>03/biofuels/quant\_biodiesel.htm [Accessed November 23, 2010].
- EURACTIV NETWORK. 2009. *Biofuels: The Next Generation* [Online]. EurActiv Network. Available: <u>http://www.euractiv.com/en/energy/biofuels-generation/article-165951</u> [Accessed November 04, 2010].
- EUROPEAN BIODIESEL BOARD. 2003-2009a. *Statistics: The EU biodiesel industry* [Online]. European Biodiesel Board. Available: <u>http://www.ebb-</u> eu.org/stats.php [Accessed November 03, 2010].
- EUROPEAN BIODIESEL BOARD. 2003-2009b. *What is biodiesel?* [Online]. European Biodiesel Board. Available: <u>http://www.ebb-eu.org/biodiesel.php</u> [Accessed November 03, 2010].
- FAO. 2010. FAOSTAT: Food and Agricultural commodities production [Online]. FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO). Available: <u>http://faostat.fao.org/site/567/default.aspx#ancor</u> [Accessed November 04, 2010].
- FARRELL, A. E., PLEVIN, R. J., TURNER, B. T., JONES, A. D., O'HARE, M. & KAMMEN, D. M. 2006. Ethanol Can Contribute to Energy and Environmental Goals. *Science*. American Association for the Advancement of Science.
- FAVA, J. A. 2002. Life Cycle Initiative: A Joint UNEP/SETAC Partnership to Advance the Life-Cycle Economy. *International Journal of Life Cycle Assessment*, 7, 196-198.

- FISCHER, G., VELTHUIZEN, H., SHAH, M. & NACHTERGAELE, F. 2002. Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results, Vienna, International Institute for Applied Systems Analysis.
- FISCHER, G., VELTHUIZEN, H. V., NACHTERGAELE, F. & MEDOW, S. 2000. Global Agro-Ecological Zones (Global AEZ). Food and Agriculture Organization of the United Nations Rome, Italy and International Institute for Applied Systems Analysis Laxenburg, Austria
- GRZEBISZ, W., ŁUKOWIAK, R., BIBER, M. & PRZYGOCKA-CYNA, K. 2010. EFFECT OF MULTI-MICRONUTRIENT FERTILIZERS APPLIED TO FOLIAGE ON NUTRITIONAL STATUS OF WINTER OILSEED RAPE AND DEVELOPMENT OF YIELD FORMING ELEMENTS. J. Elementol, 15, 477–491.
- HALL, C. A. S., BALOGH, S. & MURPHY, D. J. R. 2009. What is the Minimum EROI that a Sustainable Society Must Have? *Energies*, 2, 25-47.
- HALL, C. A. S. & DAY, J., J. W. 2009. Revisiting the Limits to Growth After Peak Oil: In the 1970s a rising world population and the finite resources available to support it were hot topics. Interest faded—but it's time to take another look. *American Scientist*. USA: Sigma Xi, The Scientific Research Society.
- HALL, C. A. S., MURPHY, D. & GAGNON, N. 2006. Order from Chaos (hopefully): A Preliminary Protocol for Determining EROI for fuels. *ASPO-USA Conference*. Boston, October 25-27.
- HALLEUX, H., LASSAUX, S., RENZONI, R. & GERMAIN, A. 2008. Comparative Life Cycle Assessment of Two Biofuels Ethanol from Sugar Beet and Rapeseed Methyl Ester. *International Journal of Life Cycle Assessment*, 13, 184–190.
- HORNE, R. E. 2009. Life cycle assessment: origins, principles and context. *In:* HORNE, R. E., GRANT, T. & VERGHESE, K. L. (eds.) *Life Cycle Assessment: Principles, Practice and Prospects.* CSIRO PUBLISHING.
- HUO, H., WANG, M., BLOYD, C. & PUTSCHE, V. 2008. Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.
- ISO 1997. ISO 14040: Environmental management Life cycle assessment -Principles and framework. *International Organization for Standardization, Switzerland.*
- JANULIS, P. 2004. Reduction of energy consumption in biodiesel fuel life cycle. *Renewable Energy*, 29, 861–871.
- JOHNSTON, M., FOLEY, J. A., HOLLOWAY, T., KUCHARIK, C. & MONFREDA, C. 2009. Resetting global expectations from agricultural biofuels. *ENVIRONMENTAL RESEARCH LETTERS*, 4, 1-9.
- KAVALOV, B. 2004. BIOFUEL POTENTIALS IN THE EU. The European Commission: Institute for Prospective Technological Studies and European Commission Joint Research Center.

- LEWIS, C. A. 1997. Fuel and Energy Production Emission Factors. *MEET Project: Methodologies for Estimating Air Pollutant Emissions from Transport.* AEA Technology.
- MCALISTER, S. & HORNE, R., E. 2009. Climate change responses: carbon offsets, biofuels and the life cycle assessment contribution. *In:* HORNE, R. E., GRANT, T. & VERGHESE, K. L. (eds.) *Life Cycle Assessment: Principles, Practice and Prospects.* CSIRO PUBLISHING.
- MORTIMER, N. D., CORMACK, P., ELSAYED, M. A. & HORNE, R. E. 2003. EVALUATION OF THE COMPARATIVE ENERGY, GLOBAL WARMING AND SOCIO-ECONOMIC COSTS AND BENEFITS OF BIODIESEL. *Final Report*. RESOURCES RESEARCH UNIT - SCHOOL OF ENVIRONMENT AND DEVELOPMENT - SHEFFIELD HALLAM UNIVERSITY.
- MULDER, K., HAGENS, N. & FISHER, B. 2010. Burning Water: A Comparative Analysis of the Energy Return on Water Invested.
- MULDER, K. & HAGENS, N. J. 2008. Energy Return on Investment: Toward a Consistent Framework. *Ambio*, 37, 74-79.
- NANAKI, E. A. & KORONEOS, C. J. 2009. COMPARATIVE LCA OF THE USE OF BIODIESEL, DIESEL AND GASOLINE FOR TRANSPORTATION. 1st International Exergy, Life Cycle Assessment, and Sustainability Workshop & Symposium (ELCAS) 4 - 6 June,. NISYROS - GREECE.
- NETHERLANDS ENVIRONMENTAL ASSESSMENT AGENCY. 2010. Serious indirect effects of some biofuels on global biodiversity and greenhouse gas emissions [Online]. Netherlands Environmental Assessment Agency. Available: <u>http://www.pbl.nl/en/news/pressreleases/2010/20100531-</u> Serious-indirect-effects-of-some-biofuels-on-global-biodiversity-andgreenhouse-gas-emissions.html [Accessed November 10, 2010].
- ODUM, H. T. 1974. Energy, Ecology, & Economics [Online]. Minnesotans For Sustainability. Available: <u>http://www.mnforsustain.org/energy\_ecology\_economics\_odum\_ht\_1973.h</u> tm [Accessed November 03, 2010].
- PURDUE UNIVERSITY. 2010. *Brassica napus L.* [Online]. Purdue University. Available:

http://www.hort.purdue.edu/newcrop/duke\_energy/Brassica\_napus.html [Accessed November 04, 2010].

- ROCKWELL, K. 2011. Alternative Energy Why do we Need it? [Online]. Available: <u>http://ezinearticles.com/?Alternative-Energy---Why-do-we-Need-it?&id=801280</u> [Accessed January 26 2011].
- SMITH, L. 2007. Rapeseed biofuel 'produces more greenhouse gas than oil or petrol'. *Times Newspapers*. Times Newspapers Ltd.
- SU, C. L. & LEE, Y. M. 2008. Development status and life cycle inventory analysis of biofuels in Taiwan. *Energy Policy*, 37, 754–758.
- THAMSIRIROJ, T. & MURPHY, J. D. 2010. Can Rape Seed Biodiesel Meet the European Union Sustainability Criteria for Biofuels? *Energy Fuels*, 24, 1720–1730.

- THE EUROPEAN COMMISSION 2005. PURSUANT TO ARTICLE 4(1) OF DIRECTIVE 2003/30/EC: on the promotion of the use of biofuels or other renewable fuels for transport. *REPORT COVERING THE YEAR 2005*.
- THE OFFSHORE VALUATION GROUP 2010. The Offshore Valuation: A valuation of the UK's offshore renewable energy resource. Public Interest Research Centre.
- VROM. 2010. *Biofuels* [Online]. Ministry of Housing, Spatial Planning and the Environment, The Netherlands. Available: http://international.vrom.nl/pagina.html?id=37483 [Accessed].
- WORLD ENERGY COUNCIL 2010. Survey of Energy Resources. London, UK.
- WORLD PETROLEUM COUNCIL. 2009. Alternative Transport Fuels Courtesy of AIP [Online]. Available: <u>http://www.world-</u> petroleum.org/index.php?/Technology/alternative-transport-fuels-courtesyof-aip.html [Accessed November 17, 2010].
- ZAH, R., FAIST, M., REINHARD, J. & BIRCHMEIER, D. 2009. Standardized and simplified life-cycle assessment (LCA) as a driver for more sustainable biofuels. *Journal of Cleaner Production*, 17, S102–S105.

## 7. APPENDICES

Appendix 1. Interview format for farmers in Dutch

# VRAGENLIJST VOOR LANDBOUWERS

Geachte Heer van Geel:

Mijn naam is Melese Tesfaye en ik ben student aan het Internationaal Instituut voor Geo-Information Science and Earth Observation (ITC). Dit is een faculteit aan de Universiteit Twente. Meer informatie over dit instituut is te vinden op www.itc.nl

Momenteel doe ik onderzoek naar energie-efficiëntie van koolzaad productie voor biobrandstof in twee Europese landen: Polen en Nederland. De productie van biobrandstof uit koolzaad levert energie maar de activiteiten en grondstoffen die gebruikt worden voor de teelt van het gewas kosten natuurlijk ook energie. Om goed inzicht te krijgen in zowel de energie input als de energie opbrengst van koolzaadteelt en biobrandstofproductie wil ik graag een aantal vragen stellen aan zowel landbouwers als biobrandstof producenten.

Hierbij wil ik u uitnodigen om mij te helpen bij mijn onderzoek door de deze vragenlijst in te vullen. Dit zal ongeveer 20 minuten tijd in beslag nemen. De resultaten van de studie kunnen indien u dat interessant vindt naar u toe worden gestuurd.

Bij voorbaat vast hartelijk dank voor uw medewerking!

Naam van de landbouwer: \_\_\_\_

Stad / Plaats: \_

- 1. Welke gewassen kweekt u op uw bedrijf (anders dan koolzaad)?
- 2. Op wat voor bodemtype(s) kweekt u koolzaad?
- 3. Hoeveel hectaren land telt uw bedrijf en hoeveel hectare gebruikt u voor de teelt van koolzaad?

4.	Hoeveel is	s de opbrengst	van koolzaad	(kg/ha) en	op welk	tijdstip	oogst u?
----	------------	----------------	--------------	------------	---------	----------	----------

- 5. Aan wie verkoopt u het door u geteelde koolzaad?
- 6. Wat is de afstand tussen uw bedrijf en het bedrijf waar de koolzaad verder verwerkt wordt?
- 7. Hoe wordt het koolzaad getransporteerd (tractor + aanhanger, vrachtwagen, anders)?
- 8. Produceert u ook stro van koolzaad of oogst u de gehele plant? Indien u stro produceert, hoeveel is dat per hectare per jaar (kg / ha / jr)?
- 9. Wat doe u met het stro?
- 10. Welk type van koolzaad landbouw gebruikt u?
  - Vruchtwisseling
  - Eens
- 11. Wat zijn de activiteiten voor de koolzaadteelt en wanneer worden die uitgevoerd?

Ploegen	
Het zaaien	
Bemesten	

s de afstand die u moet afleggen	tussen de boerderij en het veld?
oor soort brandstof gebruikt u v	oor uw tractor?
el kilometer kan u rijden op ee	n liter brandstof?
u enige steun van de overheid oor soort?	of NGO's voor koolzaad landbouw?
t u gebruik van meststoffen?	
Ja	Geen
wat voor soort meststoffen die Organische Kunstmest	u gebruikt?
	die u gebruikt?
	u enige steun van de overheid o oor soort? u gebruik van meststoffen? Ja wat voor soort meststoffen die Organische Kunstmest

20.	Wat is de hoeveelheid van de meststoffen (N, P, K, S) (kg / ha) in elke toepassing?
21.	Gebruikt u chemicaliën voor gewasbescherming? Ja Geen
22.	Zo nee, wat voor soort methode je gebruikt voor gewasbescherming?
23.	Zo ja, wat zijn de merknamen van de verschillende typen gewasbescherming?
	Herbiciden:
	Fungiciden:
	Pesticiden:
	Anders:
24.	Hoeveel keer per teeltperiode wordt gewasbescherming toegepast?
	Herbiciden:
	Fungiciden:
	Pesticiden:

19. Hoeveel keer per jaar en wanneer bemest u met kunstmest?

	Anders:
25.	Hoeveel liter per hectare wordt gegeven in het geval van gewasbescherming?
	Herbiciden:
	Fungiciden:
	Pesticiden:
	Anderen:
26.	Wat voor machine gebruikt u voor de oogst (kunt u ook de merknaam geven)?
27.	Kunt u een schatting geven van de totale hoeveel brandstof (waarschijnlijk diesel) die u per hectare nodig heeft voor het telen van koolzaad?

Hartelijk dank!

### Appendix 2. Interview format for farmers in Polish

## **KWESTIONARIUSZ (F)**

Szanowny Respondencie

Jako student Międzynarodowego Instytutu Informacji Geograficznej i Obserwacji Ziemi, chciałbym zaprosić Pana/Panią do udziału w badaniu. Posłuży ono do napisania pracy magisterskiej dotyczącej porównania wydajności energetycznej produkcji biopaliwa z rzepaku w dwóch europejskich krajach: Polsce i Holandii.

Kwestionariusz, o którego wypełnienie uprzejmie proszę Panią/Pana, dotyczy ilości energii zużywanej do uprawiania rzepaku i do produkcji biopaliwa z tej rośliny. Państwa odpowiedzi są niezbędne do zgromadzenia danych na ten temat.

Będę bardzo wdzięczny za udział w prowadzonych przeze mnie badaniach. Wypełnienie kwestionariusza zajmie Pani/Panu nie więcej niż 15-20 minut. Wyniki przeprowadzonego badania zostaną udostępnione na prośbę osoby biorącej w nim udział.

Międzynarodowy Instytut Informacji Geograficznej i Obserwacji Ziemi z siedzibą w Holandii (<u>www.itc.nl</u>) jest jednym z instytutów, w którym studiuję w ramach stypendium Erasmus Mundus. Program Informacja geograficzna i obserwacja Ziemi służący do zarządzania środowiskiem jest również realizowany na uniwersytecie w Southampton w Wielkiej Brytanii, na uniwersytecie w Lund w Szwecji i na Uniwersytecie Warszawskim w Polsce.

Pani/Pana odpowiedzi są niezwykle ważne w procesie prowadzenia badań. Zebrane dane mogą w przyszłości posłużyć do wskazywania drogi rozwoju dla ośrodków produkujących rzepak. W związku z tym, serdecznie dziękuję za wkład i czas poświęcony na ich przeprowadzenie.

#### Melese Tesfaye

Imię respondenta:	
Nazwisko respondenta:	
Kraj:	
Miasto:	Telefon:

1. Jakie inne rośliny i zboża, poza rzepakiem, uprawia Pan/Pani w swoim gospodarstwie?

•	Na jakiej klasy (klasach) glebie uprawia Pani/Pan te rośliny? (jeżeli to możliwe, proszę o dopisanie ziarnistości gleby)
	Jak duża jest powierzchnia, na której uprawia Pani/Pan rzepak (ha or km²)
	Jak duże są Pani/Pana sezonowe plony rzepaku (kg/ha)?
	Na co Pani/Pan przeznacza plony?
	na sprzedaż na użytek domowy
•	Jeżeli Pani/Pan sprzedaje, kto jest odbiorcą?
	Jak daleko od Pani/Pana gospodarstwa znajduje się miejsce wymienione w punkcie 6 ?
	W jaki sposób transportuje Pani/Pan tam zbiory?

	V jaki snosóh przetwarza E	an stome?
0. •	v jaki sposoo pizetwaiza i	an siomų:
– 1. Ja	aki rodzaj uprawy rzepaku	Pani/Pan?
	☐ monokultura	
	płodozmian	
2. Ja	akie działania Pani/Pan po	dejmuje w trakcie uprawy rzepaku?
	Oranie ziemi	
	sianie	
	Nawożenie	
	Ochrona zbóż	
	zbieranie	
	suszenie	
	składowanie	
	Inne (jakie?)	
3. C	Czy używa Pani/Pan traktor	a lub innej maszyny w swoim gospodarstwie
	Tak	nie
	· (1: 4 · 1 · · · · 1 · ( · · · · · · · · · · ·	

15.	Jak często poszczególne z wymienionych wyżej procesów są przez
	Panią/Pana wykonywane?

- 16. Jaki dystans ma Pani/Pan do pokonania między swoim gospodarstwem a polem uprawnym?
- 17. Ile kilometrów może Pani/Pan przejechać na jednym litrze paliwa?
- 18. Jakiego rodzaju paliwa używa Pani/Pan we wspomnianych maszynach?
- 19. Czy otrzymuje Pani/Pan jakiekolwiek wsparcie w uprawie rzepaku od organizacji rządowych lub pozarządzowych? Jakiego rodzaju?
- 20. Czy używa Pani/Pan nawozów?

🗌 Tak
-------

	Nie
--	-----

21. Jeżeli tak, jakiego są one rodzaju?

Naturalne
Sztuczne

23.	Jezeli korzysta Pani/Pan ze sztucznych nawozow, ile razy w roku są one używane?
24.	Jaka jest proporcja zużywanych nawozów (NPK) (kg/ha) w każdym przypadku ich używania?
25.	Czy używa Pani/Pan środków ochrony roślin?
	Tak Nie
26.	Jeśli nie, w jaki sposób chroni Pani/Pan uprawy rzepaku?
27.	Jeśli tak, jakiej marki środków ochrony roślin Pani/Pan używa?
	Herbicydy:
	Fungicydy:
	Pestycydy (środki insektobójcze)
	Inne (jakie?):

	Herbicydy:				
	Fungicydy				
	Pestycydy (środki insektobójcze):				
	Inne (jakie?):				
29.	Jaka jest proporcja (l/ha) stosowanych środków ochrony roślin (koncentrat)				
w ciągu jednego użycia?					
	Herbicydy:				
	Fungicydy				
	Pestycydy (środki insektobójcze):				
	LII Inne (jakie?):				

- 30. Używa Pan/Pani ludzi czy maszyn przy zbiorach?
- 31. Jeżeli używa Pani/Pan maszyn, jakiej marki są to maszyny?
- 32. Jak dużo paliwa (najprawdopodobniej diesel) Pani/Pan zużywa na pracę tej maszyny (na godzinę lub na hektar pracy)?

Dziękuję



# Appendix 3.<sup>19</sup>Country based EROEI map analysis









	Yield (ton/ha)		EROEI	
Country	Average Maximum	Average Minimum	Average Maximum	Average Minimum
Austria	2.46	1.73	1.63	1.23
Belgium	2.13	1.41	1.55	1.14
Bulgaria	2.18	1.36	1.62	1.17
Cyprus	1.33	0.58	1.22	0.65
Czech Republic	3.02	2.22	1.94	1.62
Denmark	2.99	2.15	1.91	1.54
Estonia	1.72	1.06	1.31	0.84
Finland	1.94	1.05	1.56	1.04
France	2.19	1.41	1.62	1.19
Germany	2.87	2.06	1.86	1.49
Greece	1.69	0.88	1.39	0.85
Hungary	2.59	1.81	1.77	1.39
Ireland	1.15	0.30	1.15	0.48
Italy	1.78	1.01	1.40	0.89
Latvia	3.89	3.11	2.19	1.96
Lithuania	3.83	3.05	2.17	1.92
Luxembourg	1.50	0.52	1.36	0.69
Malta	4.43	3.64	2.37	2.18
Netherlands	1.58	0.80	1.34	0.80
Poland	2.67	1.82	1.78	1.35
Portugal	1.68	1.01	1.33	0.85
Romania	2.35	1.53	1.69	1.27
Slovakia	2.24	1.42	1.61	1.15
Slovenia	2.39	1.56	1.67	1.22
Spain	1.68	0.98	1.33	0.83
Sweden	1.83	1.01	1.45	0.93
United Kingdom	1.88	1.10	1.49	1.01
Switzerland	2.60	1.86	1.71	1.32
West Europe	2.45	1.66	1.70	1.29

Appendix 4. Average maximum and minimum yield and EROEI of each country in Europe from yield and EROEI maps

East Europe	2.53	1.71	1.75	1.33
North Europe	2.30	1.50	1.62	1.17
South Europe	1.73	0.99	1.37	0.86
Europe	2.27	1.49	1.62	1.18