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Biomass: hot or not?
Extended techno-economic assessment of Energy Conversion Parks

Proefschrift voorgelegd tot het behalen van de graad van doctor in de Toegepaste Economische Wetenschappen, te verdedigen door:

Miet Van Dael

Promotor: Prof. dr. ir. Steven Van Passel

universiteit hasselt

KNOWLEDGE IN ACTION

MEMBERS OF THE JURY

Prof. dr. ir. Steven Van Passel (promotor)
Research group of environmental economics
Center for Environmental Sciences (CMK) - Hasselt University

Prof. dr. Piet Pauwels (chairman)
Research group of marketing and strategy - Dean
Hasselt University

Prof. dr. Gilbert Swinnen
Research group of marketing and strategy
Hasselt University

Prof. dr. Bernard Vanheusden
Faculty of law
Center for Environmental Sciences (CMK) - Hasselt University

dr. Tom Kuppens
Research group of environmental economics
Center for Environmental Sciences (CMK) - Hasselt University

dr. Nele Witters
Research group of environmental economics
Center for Environmental Sciences (CMK) - Hasselt University

Prof. dr. ir. Jeroen Buysse
Department of agricultural economics
Ghent University

dr. ir. Calliope Panoutsou
Faculty of natural sciences, Centre for environmental policy
Imperial College London

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SUMMARY

Biomass is one of the most versatile sources of renewable energy and essential in attaining the 20-20-20 targets imposed by Europe. Biomass allows producing biofuels, electricity and heat. Besides, one can produce high value products from biomass, such as chemicals. However, for these purposes it is important to use biomass residue streams which are nowadays not or inefficiently used. As such, it is possible to avoid competition with food or feed. Next to the advantages such as versatility, biomass also has some disadvantages: it is often geographically dispersed, waste streams have a high moisture content, low energy density, and biomass typifies itself by seasonal variations. To counteract these disadvantages an Energy Conversion Park (ECP) can provide a solution. An ECP is a specific form of a biorefinery in which focus lies on regional residue streams. An ECP combines diverse sources of local biomass residue streams and converts them using a combination of technologies into energy and materials.

For the development of an ECP a ten-step procedure is developed which allows screening all regional possibilities and as such increases chances of implementation. Important is that all stakeholders are involved during the whole procedure in order to increase chances of acceptance. Starting point is the selection of a location. At this location, local support is created, an inventory is made of all local biomass residue streams and the demand of heat. Based on this inventory ECP concepts are set up that match local demand and supply and that optimize the utilization of these residue streams. The concepts are presented to the involved stakeholders. Those concepts which contribute most to the local situation, will be analyzed using an extended techno-economic assessment (TEA) in order to get a clear idea of the risks that potential investors may have. Based on that analysis a decision will be taken on the implementation. The practicability of the procedure is proven by the decision in 2013 to implement one of the cases which was analyzed within this dissertation.

When developing an ECP, often no location has been chosen or is chosen based on one or a limited number of criteria. In order to facilitate the location choice, a macro screening method is developed (Chapter 2). The method allows reducing the number of locations based on a rough, but substantiated estimation. First it is determined on which criteria a location will be judged. Afterwards information is collected, which provides a certain score on each criterion. To the different criteria also a score is granted. Not every criterion is equally important. The score and weight are multiplied to form an end score. The higher this final score, the more interesting a location is. This Multicriteria Analysis (MCA) is combined with a Geographic Information System (GIS). The different steps run in parallel and as a consequence of learning during the process, some steps may have to be executed again. The result of the macro screening is a substantiated selection of potential interesting locations.

When the location is selected and an inventory is made of the local available biomass residue streams, some ECP concepts are presented to the involved stakeholders. The ECP concepts which contribute most to the regional economy are further subjected to an extended TEA (Chapter 3 and Chapter 4). This assessment is essential in the further development of biobased technologies. By integrating the technological and economic analysis (Chapter 3) it is possible to get a clear idea of the parameters which influence the economic feasibility most. From the case studies it is concluded that investment costs and operational costs are high and that revenues are rather limited. Costs are high due to the fact that the innovative technologies require investments that allow for the integration in the existing infrastructure. Revenues are limited due to the fact that buyers are not always (immediately) convinced of the quality and applicability of the innovative, biobased materials. However, high value products are essential in order to ensure the economic feasibility of ECP concepts. Also, it is important to have a clear picture of the parameters that need further improvement in order to have a good insight into the risks linked to the investment.

Next to the techno-economic analysis, also a sustainability analysis has to be performed within the extended TEA (Chapter 4). Important is to know whether the produced materials within an ECP can be taken into account in order to attain the 20-20-20 targets imposed by Europe. To this end, the guidelines provided by the Renewable Energy Directive (RED) can be used. However, focus still lies on unidimensional, energy-related processes. Within the guidelines of the RED some simplifications are implemented in order to increase the practical manageability. But, this goes side by side with a decrease in accuracy. Moreover, several decisions are rather unclear. As shown in the case study, these decisions do have a fundamental impact on the end results and can imply that some products cannot be taken into account to attain the European targets. Ambiguities exist concerning the state of waste, which is given to products, the allocation procedure, and the boundaries of the process that are taken into account. From the study, it is clear that the guidelines are less applicable within the boundaries of the biobased economy in which focus on materials even increases.

When investors decide, based on the previous steps to implement a biomass project, social obstructions can hinder implementation. Since it is not always clear why these effects arise, a study was done to get insight into the perception, knowledge and attitude concerning biomass (Chapter 5). From the study it seems that the respondents' level of knowledge concerning renewable energy and especially bioenergy is very low. This can be explained by the limited time that is spent on renewable energy in the current curricula of secondary education. From the study it seemed that providing more information using a lecture, raises the knowledge level significantly on a short term basis. Moreover, the perception concerning biomass is positively influenced by the provision of more information. Respondents indicated that biomass could help in reducing greenhouse gas emissions and that the government should support research and development concerning biomass after being informed. Furthermore, the respondents do not perceive wood as an interesting source for energy. Note that it is expected that biomass residue streams will gain importance in the future. After providing a lecture, the respondents were more willing to use biomass in their daily activities. However, they were less willing to learn more about biomass. This can be due to the chosen format and, therefore, it is important to search for alternative ways to provide more information about biomass to raise acceptance.

SAMENVATTING

Biomassa is een van de meest veelzijdige bronnen van hernieuwbare energie en onontbeerlijk in het behalen van de 20-20-20 doelstellingen opgelegd door Europa. Biomassa laat toe om zowel biobrandstoffen, elektriciteit als warmte te produceren. Daarnaast is het ook mogelijk om uit biomassa meer hoogwaardige producten zoals chemicaliën te produceren. Het is echter belangrijk om voor deze producten te vertrekken vanuit biomassareststromen die vandaag moeilijk of niet gevaloriseerd worden. Op die manier kan bijvoorbeeld de competitie met voedsel of voeder vermeden worden. Naast de voordelen zoals veelzijdigheid heeft biomassa ook enkele nadelen: het is vaak geografisch erg verspreid, heeft een hoog vochtgehalte en lage energiedichtheid en typeert het zich door seizoenschommelingen. Om deze nadelen te compenseren biedt een Energieconversiepark (ECP) een oplossing. Dit is een bijzondere vorm van een bioraffinaderij waarbij de focus ligt op regionale reststromen. Een ECP combineert verschillende bronnen van lokale biomassa reststromen en verwerkt deze met behulp van een combinatie van conversietechnologieën tot energie en materialen.

Voor het ontwikkelen van een ECP werd een tien-stappen procedure ontwikkeld die toelaat om alle regionale mogelijkheden te screenen en de kans op implementatie te vergroten. Belangrijk is dat tijdens de procedure alle stakeholders betrokken worden om op die manier de acceptatie te vergroten. Er wordt gestart vanuit het selecteren van een locatie. Hier wordt lokale ondersteuning gecreëerd en een inventaris gemaakt van alle lokale biomassareststromen en de vraag naar warmte. Op basis van die inventarisatie worden een aantal ECP configuraties, die de lokale vraag en het aanbod op elkaar afstemmen en die de stromen optimaal benutten, voorgelegd aan de betrokken stakeholders. De concepten die het meest kunnen bijdragen aan de lokale situatie worden onderworpen aan een uitgebreide techno-economische analyse (TEA) om zo een inschatting te maken van de risico’s die potentiële investeerders lopen. Op basis van die analyse zal uiteindelijk een business case

verder geïmplementeerd worden. De praktische toepasbaarheid van deze procedure is gebleken uit de beslissing tot concrete implementatie van een van de uitgewerkte cases binnen dit doctoraat in 2013.

Bij de ontwikkeling van een ECP is er vaak nog geen locatie geselecteerd of is de locatie geselecteerd op basis van één of een beperkt aantal criteria. Om de locatiekeuze te faciliteren werd een macro screening methode ontwikkeld (Hoofdstuk 2). Deze methode laat toe om het aantal potentieel interessante locaties te reduceren op basis van een ruwe, maar gestructureerde, inschatting. Eerst wordt bepaald op basis van welke criteria een locatie beoordeeld kan worden. Daarna wordt er informatie verzameld, wat een bepaalde score geeft voor ieder criterium. Aan de verschillende criteria worden ook gewichten toegekend. Niet elk criterium is immers even belangrijk in de eindbeoordeling. De score en het gewicht worden vermenigvuldigd ter vorming van een eindscore. Hoe hoger de eindscore, hoe interessanter de locatie. Deze multicriteria analyse (MCA) zal gecombineerd worden met een geografisch informatiesysteem (GIS). De verschillende stappen kunnen parallel lopen en als gevolg van continu leren tijdens het proces zullen fasen eventueel opnieuw uitgevoerd moeten worden. Het resultaat van de macro screening is een onderbouwde selectie van de potentieel meest interessante locaties.

Wanneer de locatie gekozen is en een inventaris gemaakt is van de lokaal beschikbare biomassareststromen, worden een aantal ECP-concepten voorgelegd aan stakeholders. De ECP-concepten die de grootste bijdrage leveren aan de regionale economie, worden verder onderworpen aan een uitgebreide TEA (Hoofdstuk 3 en Hoofdstuk 4). Deze analyse is onontbeerlijk in de ontwikkeling van biogebaseerde technologieën. Door de integratie van een technologische en economische analyse (Hoofdstuk 3) is het mogelijk een goed beeld te krijgen van de parameters die de economische haalbaarheid het meest beïnvloeden. Uit de case studies blijkt dat investeringskosten en operationele kosten erg hoog zijn en dat opbrengsten die hier tegenover staan eerder beperkt blijven. Kosten zijn hoog doordat zowel geïnvesteerd moet worden in nieuwe technologieën, als in installaties die toelaten om het geheel in te passen in de bestaande infrastructuur. Opbrengsten blijven vaak beperkt doordat afnemers niet altijd (onmiddellijk) overtuigd zijn van de kwaliteit en toepasbaarheid van de innovatieve, biogebaseerde materialen. Echter zijn hoogwaardige producten essentieel om de economische haalbaarheid van ECP concepten te verzekeren. Het is om deze redenen dan ook belangrijk om een goed beeld te hebben van de parameters die verder verbeterd moeten worden en zo een duidelijk beeld te schetsen van de risico’s verbonden aan de investering.

Naast een techno-economische analyse moet ook de duurzaamheid van ECP concepten nagegaan worden binnen een uitgebreide TEA (Hoofdstuk 4). Belangrijk is om te weten of producten die geproduceerd worden binnen een ECP in aanmerking kunnen komen voor het behalen van de 20-20-20 doelstellingen van Europa. Hiervoor kunnen de richtlijnen zoals voorgeschreven in de Renewable Energy Directive (RED) gehanteerd worden. Echter ligt de nadruk hier nog steeds op unidimensionale, energiegerelateerde processen. Binnen de richtlijnen van de RED werden enkele vereenvoudigingen doorgevoerd om de praktische hanteerbaarheid te verhogen. Dit gaat echter ten koste van nauwkeurigheid. Bovendien blijven een aantal beslissingen eerder onduidelijk. Zoals aangegeven in de gevalstudie hebben deze beslissingen wel een fundamentele impact op het eindresultaat en kunnen deze als resultaat hebben dat bepaalde producten niet meegerekend kunnen worden voor het behalen van de Europese doelstellingen. Onduidelijkheden bestaan omtrent de status afval, die al dan niet toegekend moet worden aan producten, de allocatie-procedure, en de grenzen die in rekening genomen moeten worden. Uit de studie werd dan ook duidelijk dat de richtlijnen minder hanteerbaar zijn binnen de grenzen van een biogebaseerde economie waarin het belang van materialen nog meer toeneemt.

Wanneer investeerders op basis van voorgaande stappen overgaan tot de concrete implementatie van biomassaprojecten, kan heel wat sociale tegenstand verwacht worden. Doordat het niet altijd duidelijk is waarom deze effecten optreden, werd nagegaan wat de perceptie, kennis en houding is tegenover biomassa (Hoofdstuk 5). Uit de studie blijkt dat de kennis over hernieuwbare energie en in het bijzonder over bioenergie erg laag is bij de respondenten. Dit kan verklaard worden doordat hernieuwbare energie slechts in beperkte mate in de huidige curricula van secundair onderwijs opgenomen is. In de studie werd ook aangegeven dat door het geven van meer informatie tijdens een les, deze kennis significant verhoogd werd op korte termijn. Bovendien werd de perceptie over biomassa op een positieve wijze beïnvloed door het geven van extra informatie. Respondenten zijn na het geven van informatie van mening dat biomassa kan helpen om de broeikasgasemissies te laten dalen en vinden dat de overheid onderzoek en ontwikkeling in het kader van het gebruik van biomassa moet ondersteunen. De respondenten zien hout echter niet als een interessante bron voor bioenergie. We verwachten ook dat voornamelijk biomassa reststromen aan belang zullen toenemen in de toekomst. Na het geven van de les waren respondenten ook meer bereid om bioenergie te gebruiken in hun dagelijks leven. Echter waren de respondenten minder bereid om meer te leren over biomassa na het geven van de les. Het gekozen format kan hier een belangrijke rol spelen en het is dan ook belangrijk om te zoeken naar alternatieve manieren om kennis over biomassa te verspreiden en op die manier de aanvaarding te verhogen.

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AHP	Analytical hierarchy process
AVE	Average variance extracted
B-SAT	Bioenergy sustainability assessment tool
CBA	Cost benefit analysis
CE	Column element
CEC	Cumulative exergy content
CEENE	Cumulative exergy extraction from the natural environment
CF	Cash flow
CHP	Combined heat and power
CI	Consistency index
CR	Consistency ratio
DEA	Data envelopment analysis
DM/dm	Dry matter
DPBP	Discounted payback period
EC	European Commission
ECP	Energy conversion park
ELECTRE	Elimination and choice expressing reality
EoW	End-of-waste
EU	European Union
FER	Fossil energy requirement
FTE	Full time equivalent
GHG	Greenhouse gas
GIS	Geographical information system
GJ	Gigajoule
GWP	Global warming potential
HHV	Higher heating value
IRR	Internal rate of return
LBM	Liquid biomethane
LCA	Life cycle assessment
LHV	Lower heating value

LNG	Liquid natural gas
MAVT	Multi-attribute value theory
MCA	Multicriteria analysis
MCDA	Multicriteria decision analysis
MFA	Material flow analysis
MFD	Material flow diagram
MGA	Multigroup analysis
MSW	Municipal solid waste
NPV	Net present value
OMSW	Organic municipal solid waste
PBP	Payback period
PLS	Partial least squares
RE	Row element
RED	Renewable energy directive
RO	Reversed osmoses
SEM	Structural equation modeling
TEA	Techno-economic assessment
UASB	Upflow anaerobic sludge bed
UF	Ultrafiltration
VAF	Variance accounted for
VIF	Variance inflation factor
VITO	Vlaams instituut voor technologisch onderzoek
WACC	Weighted average cost of capital
WSM	Weighted sum method

Chapter 1.

Introduction[*]

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1.1. Introduction

European policy states that by 2020 at least 20% of final energy consumption should emanate from renewable sources (EC, 2009). Moreover, the European Commission proposes an objective of increasing the share of renewable energy to at least 27% of the EU's energy consumption by 2030 (EC, 2014). Biomass cannot be disregarded in order to attain this target and will also enhance energy security in the EU (Panoutsou, Eleftheriadis, & Nikolaou, 2009). Moreover, biomass is currently the most abundant and versatile form of renewable energy in the world, generating electricity, heat and biofuels (IEA, 2012; JRC, 2011; Kalt & Kranzl, 2011; Valdez-Vazquez, Acevedo-Benítez, & Hernández-Santiago, 2010). Many studies have been performed to investigate the actual potential of biomass at different levels (e.g. Global, European, Country) and using multiple methodologies (de Wit & Faaij, 2010; Faaij, Steetskamp, van Wijk, & Turkenburg, 1997; Smeets, Faaij, Lewandowski, & Turkenburg, 2007; Thrän, Seidenberger, Zeddies, & Offermann, 2010). As such, estimations vary between close to zero and satisfying the world energy demand multiple times (Thrän et al., 2010). Therefore, the efficient use of biomass for energy is important in our aim to produce renewable energy. Biomass residue streams (e.g. verge cuttings, the organic fraction of municipal solid waste and by-products of agriculture) are largely available, but are hardly or inefficiently used. For example in Flanders the total amount of organic municipal solid waste collected was 338,000 ton in 2011 (Braekevelt & Schelfhout, 2013). For e.g. verge cuttings no clear inventory has yet been made due to the unavailability of data. These streams do not compete with food or feed and can be regionally collected to avoid high supply costs. However, in Western European countries, the focus currently lies on the use of biomass streams which are clean and pure, like wood pellets, often imported over large distances. The energy conversion plants are mostly one-dimensional, *i.e.* they are specifically dedicated to one biomass input source, rely on the most appropriate conversion technology for that type of biomass and produce a specific output like biofuels or electricity and/or heat. As a consequence, in many areas demand for woody residues as an energy resource is steadily increasing, leading to competition on the market. Therefore, local biomass initiatives should mainly focus on wet biomass, which are more difficult to handle and transport and therefore require local solutions. Nevertheless, authors in recent studies point to the potential of biomass residue streams and the many benefits they can include (Cheng et al., 2012; Kravanja, Modarresi, & Friedl, 2013). For example, Igliński et al. (2012) stressed the potential and benefits of using unmanaged biomass such as manure, maize after seed harvest and organic municipal solid waste. Ali, Nitivattananon, Abbas, and Sabir (2012) showed the potential of green waste from green markets in Thailand. Tonini and Astrup (2012) conclude their study with the recommendation to use residual, domestically available biomass instead of energy crop produce. Note that depending on the region, different biomass sources are available in different amounts. Scholars also investigated the possibilities of using regionally available biomass streams in local decentralized energy generation systems. They concluded that these systems offer many advantages such as more efficient usage of end products (e.g. electricity, heat, cooling, fertilizer), reduction of logistics and regional development (Chicco & Mancarella, 2009; Freppaz et al., 2004; D. P. Papadopoulos & Katsigiannis, 2002). The search for a well-suited location is as a consequence vital but not straightforward. Having a starting point (e.g. existing conversion facility) and anchor point (*i.e.* leading organization) makes the entire implementation process more specific and effective. Since transport should be regionally organized, accessibility to the location should also receive sufficient attention. At the same time, symbiosis with existing local activities (e.g. demand for biomass output products) has to be identified. The focus on regionally available biomass sources will reduce the production cost of bioenergy (Gan, 2007). Allen, Browne, Hunter, Boyd, and Palmer (1998) estimated 20-50% of the biomass delivered cost to be coming from transport and handling. Moreover, a regional approach will reduce the uncertainty concerning the biomass potential. Local circumstances can be taken into account, leading to more accurate estimations (Schlager, Krismann, & Schmieder, 2010). By simultaneously using various types of biomass the energy production plant's long term supply is ensured and potential problems (e.g. seasonal fluctuations, price rise) can be circumvented (Boukis, Vassilakos, Kontopoulos, & Karellas, 2009). Furthermore, economies of scale and economies of scope can be achieved by using multibiomass energy flows. The difference between both is that economies of scale are obtained by increasing the size or scale of an installation as the fixed costs can be spread over more units of output, whereas economies of scope are achieved when it is less costly to combine two or more product lines in one firm than to produce the outputs in separate firms. Also note that both concepts are not directly linked. It is for example possible to obtain economies of scope, even if the production process involves diseconomies of scale (Bernheim & Whinston, 2008). In terms of biomass economies of scale can for example be achieved when more manure can be digested in one installation. Note, however, that the optimal amount is limited due to physical parameters. Economies of scope can be achieved when for example electricity as well as materials such as chemicals or proteins can be produced.

1.1.1. Site selection

Many researchers developed methodologies in order to optimize site selection in order to reduce transport and handling cost. For example Voets, Neven, Thewys, and Kuppens (2013) investigated, based on GIS-knowledge, which of three pre-identified locations would be most suitable for a biomass plant, taking into account the spatial distribution of the contaminated willow supply and the total cost of willow transport. Also Höhn, Lehtonen, Rasi, and Rintala (2014) use a GIS-based methodology to determine sites for biogas plants. However, a sound screening approach, based on multiple criteria, to determine optimal localization within a minimum time span for regional multibiomass valorization is still lacking. Current site selection approaches take too much time when applied in a large area and ask for detailed information, note that time and data gathering also cost a lot of money. On top, logistics are also dependent on the region. Therefore, the regional context has to be regarded case by case when developing biomass projects. Optimal site location is not only important for biomass supply, also heat cannot be transported over large distances and should, preferably, be used locally. Additionally, De Meester et al. (2012) pointed out that the utilization of the generated heat is even necessary to achieve an environmentally competitive technology. Heat that results from one process can for example be transported to another process where it can be used beneficially, e.g. for drying biomass (Gebrezgabher, Meuwissen, Prins, & Lansink, 2010). Also Song, Starfelt, Daianova, and Yan (2012) demonstrated that the integration of combined heat and power (CHP) plants with other processes represents a big potential in terms of reducing greenhouse gas (GHG) emissions, increasing energy utilization efficiency and replacing conventional power plants. Processes can even be further integrated by using residues, other than heat, in another process (Daianova, Dotzauer, Thorin, & Yan, 2012). In literature a combination of technologies is often called a biorefinery, which is defined as a facility that integrates biomass conversion processes to produce fuels, power and chemicals from biomass (Demirbas, 2009). However, not every nation has already recognized the large potential of biorefineries (Himadri Roy, 2011). This implies more research is needed in order to stimulate a transition towards a biobased economy. In the European strategy only the bioeconomy is described. The bioeconomy includes all activities associated with the production of biomass and the various ways in which this biomass and its residual streams are subsequently used (EC, 2012). Following this description, the biobased economy can be described as the part of the bioeconomy in which biobased products and materials are made and biomass is used in processes. It does not include the use of biomass for feed or food purposes (Vlaamse Overheid, 2013).

1.1.2. Energy conversion park

To facilitate the efficient use of regionally available biomass residue streams and to help stimulate a transition towards a biobased economy, the Energy Conversion Park (ECP) concept is developed. A biomass ECP is defined as a synergetic multidimensional biomass conversion site with a highly integrated set of conversion technologies in which a multitude of regionally available biomass (residue) sources are converted into energy and materials. A graphical representation is provided in Figure 1. An important aspect is the existence of synergies between different input streams, conversion technologies and outputs with the goal of attaining economic benefits. Another important aspect is that the outputs, *i.e.* energy and materials, can preferably be used regionally.

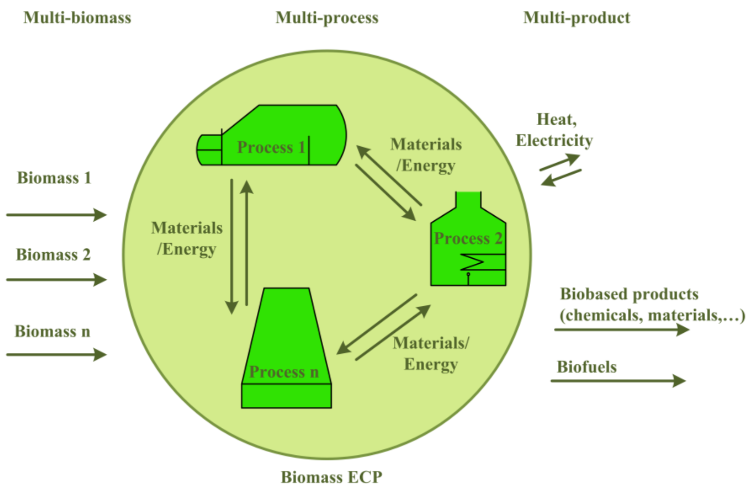

Figure 1. Schematic representation of the Energy Conversion Park concept

An ECP can be regarded as a specific form of a biorefinery in which the focus lies on the use of regional waste streams. As such, a biomass ECP answers the questions raised by authors to focus on an integrated approach using regional residue streams, as mentioned above. Further advantages derived from the regional nature of the input are: (1) the reduction of environmental impact due to the possible saving of fossil energy with related greenhouse gas savings, (2) the shortening of the transport distance resulting in lower costs, pollution and traffic burden, and (3) the creation of economic value for the local community by valorizing residual streams that do not yet have an economically interesting destination. Figure 2 provides a general overview of the potential biomass inputs and technologies that can be combined to form ECP routes and their potential outputs. Every combination of inputs, technologies, and outputs that is feasible fits the definition above. Typically in an ECP, combinations are made of technologies that exchange energy and materials in an intelligent way resulting in valuable synergies. Smart combining and linking of biomass processes contributes to efficient biomass valorization. Other scholars have previously offered an overview of biomass conversion routes. For example Bram, De Ruyck, and Lavric (2009) give an overview of the most important biomass conversion routes for transport, heat and power production, Demirbas (2009) reviews biofuel valorization facilities and biorefineries and Srirangan, Akawi, Moo-Young, and Chou (2012) gives a summary of conversion routes associated with biorefinery.

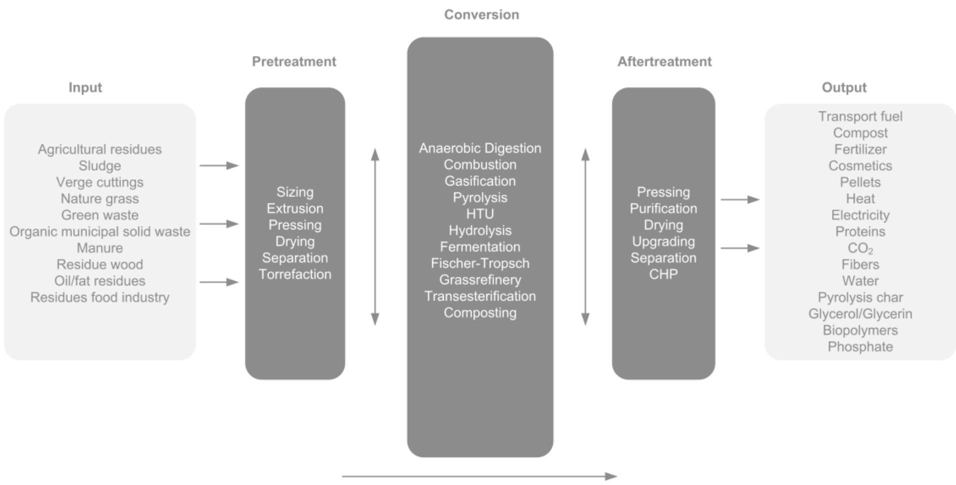

Figure 2. General overview of potential biomass ECP routes

1.1.3. Extended techno-economic assessment

In order to stimulate the interest of investors and policy for an ECP, a balance should be found between the innovative character and the techno-economic feasibility and realizability of the biomass ECP. Note that in practice technological choices are often determined by existing legislation and regional subsidy systems (Maes and Van Passel, 2012). This balance can also be achieved by providing ECP scenarios (*i.e.* combination of technologies) which will allow including more innovative technologies later. However, current analysis methods cannot answer this kind of reasoning since they do not incorporate an integrated evaluation method. Often, the scope of research is too narrow and focus is put on one aspect only, *i.e.* technical, economic, or environmental. Due to this limited focus choices are insufficiently substantiated. For example Dhar, Nakhla, and Ray (2012) perform a techno-economic evaluation in order to determine whether it is interesting to implement a pre-treatment step to enhance anaerobic digestion. However, no risk analysis is performed in their study. Fazio and Monti (2011) investigated the environmental impact of several bioenergy production systems and Starr, Gabarrell, Villalba, Talens Peiro, and Lombardi (2014) made an inventory of potential CO_2 savings through biomethane generation from municipal waste biogas using different technologies. Both studies ignored economic aspects. Although the term 'techno-economic assessment' has risen significantly since 2010, no clear definition or practical guidelines exist. Moreover, the term is often used incorrectly. For example, Uris, Linares, and Arenas (2014) and Aydiner et al. (2014) claim to perform a techno-economic analysis. However, in practice they perform a separate technical and economic analysis. This implies that it cannot be determined whether technical or economic parameters are most important for the economic feasibility. This also implies that researchers perform a technical optimization first and afterwards an economic optimization. As a consequence researchers cannot determine on which technical parameters they should focus in order to enhance the chances of actual implementation. This implies that the likely possibility exists that technical optimizations are executed on parameters that have a negligible influence on the economic feasibility and that the costs can become substantial. Moreover, by doing so no evaluation is yet made of the environmental sustainability of the process. However, in case of bioenergy this is important since subsidies can for example best be provided to technologies that allow producing energy products that can be taken into account for attaining the 20-20-20 EU targets. In order to check whether products can be taken into account for these targets, one can use the guidelines prescribed by the Renewable Energy Directive (RED). However, focus within the RED is on energy products, whereas in a biobased economy, also material is produced. Therefore, it is interesting to also search for alternative methodologies to analyze the environmental sustainability of ECP processes.

1.1.4. Social acceptance

Furthermore, the public opinion has become an increasingly important predictor of investments of various kinds (Badera & Kocoń, 2014). Therefore, public support is crucial for the EU in order to meet its targets for renewable energy and the promotion of bioenergy. Nevertheless, public opposition is a key factor in hindering bioenergy development (Paul Upham, Shackley, & Waterman, 2007). Upreti (2004) argues that developers of biomass energy projects face serious public opposition. Kaldellis, Kapsali, and Katsanou (2012) note that the positive views for renewable energy sources may change considerably when moving from global to local. Also Rösch and Kaltschmitt (1999) argue that non-technical barriers can have significant negative impacts on the overall costs of biomass-based energy projects. Furthermore, they note that these non-technical barriers can cause significant time delays resulting in a further increase of the costs. In addition, from the study of Upham and Shackley (2007) it can be concluded that participants are in favor of renewable energy in general, however, the participants questioned the environmental friendliness of bioenergy. These debates might be the results of the heterogeneous nature of biomass. Several distinct energy sources are collectively called biomass (e.g. manure, energy crops, and wood) and these distinct types vary in their availability, suitability for use in different production processes, and in terms of sustainability. Thus, while people seem to be unfamiliar with the use of biomass as an energy source, the information they receive about the use of biomass is complex, mixed and sometimes contradictory (van den Hoogen, 2007). Moreover, information concerning biomass energy projects seems to be mainly provided via the media. The mass media play a pivotal role in shaping public opinion through television, radio, and the press. Television in particular has been shown to be a powerful instrument for changing public attitudes (Halder, Havu-Nuutinen, Pietarinen, & Pelkonen, 2011; Sudarmadi et al., 2001). Furthermore, it has been found that media are most influential in shaping public attitudes toward problems that the mass public does not have regular direct or meaningful contact with (Yin, 1999). Also Wright and Reid (2011) notice that the media's discourse plays a great role in shaping public perception of controversial issues, which could influence the level of public awareness and acceptance of bioenergy. Studies exist that elaborate on the information needed in order to enhance the understanding of biomass energy generation (Rösch & Kaltschmitt, 1999; Tagashira & Senda, 2011). van der Horst (2007) indicate that risk perception of the new and unfamiliar is an important factor in peoples' dislike of a proposed wind farm. However, with actual experience of the impact of a wind farm, this reason for opposition disappeared. On top, Howell, Shackley, Mabon, Ashworth, and Jeanneret (2014) indicate that trust is most important when knowledge is low. The public's willingness to accept uncertainty is often linked to the trust that they have in the organizations, institutions and individuals that are developing and promoting the technology. Therefore, the authors argue in favor of (1) providing the public with broad-based, balanced and trustworthy information and (2) taking the full range of factors that influence public perceptions seriously. Moreover, Ter Mors, Weenig, Ellemers, and Daamen (2010) show that information can best be provided through collaboration between different stakeholders as such information is perceived to be of higher quality, more balanced and therefore of greater value. Political factors (e.g. subsidies and legislation) also play a crucial role when trying to overcome the social barriers to the use of renewable energy (Qu et al., 2012). Segon, Støer, Domac, and Yang (2004) indicate that the understanding of public perceptions, attitudes and knowledge about energy and environmental technologies and programs, constitute a framework against which strategies and policies, that encourage the use of new technologies, can be evaluated. The United Nations (UN, 2005) state that 'education, in addition to being a human right, is a prerequisite for achieving sustainable development and an essential tool for good governance, informed decision-making and the promotion of democracy. Therefore, education for sustainable development strengthens the capacity of individuals to make judgments and choices in favor of sustainable development'. Stoney et al. (1995) confirm that teaching people about the importance of the environment is central to its future protection. Environmental education is one of the most effective strategies for increasing public environmental perception, knowledge, awareness, and attitude. Therefore, education is a powerful tool for social change and plays a critical role in the development of the renewable energy industry. In general, children are more open than adults to new subjects (Karatepe, Neşe, Keçebaş, & Yumurtacı, 2012) and it has long been established that children can have an influence on their parents' purchasing and other behavioral decisions (Fell & Chiu, 2014; Wilson & Wood, 2004). Furthermore, children also pass part of the information of the everyday knowledge they get from school to their parents (Zografakis, Menegaki, & Tsagarakis, 2008).

From the above, it can be concluded that for the development of a biomass ECP concept several steps have to be taken before one can implement an installation. An integrated evaluation procedure has to be followed in order to make the right decisions when passing through these steps. The different steps for the development of a biomass ECP are described in the next section.

1.2. General development process

A biomass ECP development process is not straightforward and can be hindered or even obstructed in various steps of the process. E.g. due to its multidimensional character the set-up of an ECP requires a multitude of stakeholders with a mutual goal. From an organizational point of view it is key to keep all stakeholders goal-focused. Stakeholders aiming for different goals can easily hinder a successful completion of an ECP concept. Based on the results of multiple pilot cases, a general 10-step development process can be identified (Figure 3). This development process contains all elements described in the introduction and is largely dependent on the support and willingness of local parties to participate.

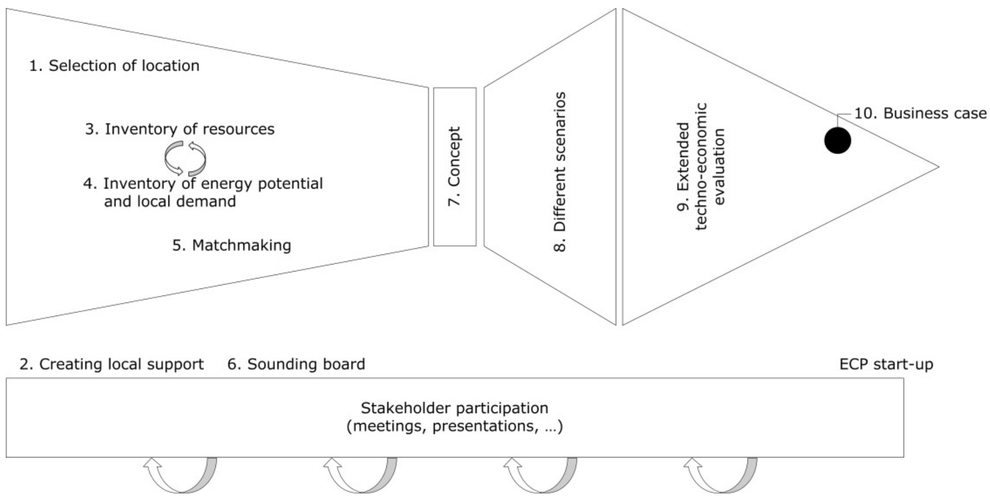

Figure 3. Step-by-step procedure for the implementation of an ECP concept

The first step is the biomass ECP location selection. Often, the location is already determined by a lead organization at an early stage. If needed, a macro screening approach can be used to determine interesting potential locations for biomass valorization. Once the location is selected, a detailed micro screening of the area is needed. In this second step, local authorities and industrial partners are contacted to gauge their interest in participating. In a third step, the biomass resources are inventoried. In making an inventory, the feasibility (*i.e.* theoretical, technical, economic and implementation (Smeets et al., 2007)) of a variety of biomass residue streams should be determined. Many articles focus on the technical potential, however, for the development of a specific biomass ECP, the implementation potential is needed. The technical potential only takes into account technical aspects of the biomass stream, such as transportability and harvesting ability. The implementation potential, though, additionally includes economic and legislative constraints. Therefore, the quantities available, material specifications, and the conditions for material supply must be specified. Afterwards, an inventory of the type and amount of local energy supply and demand is made. This fourth step is crucial for the economic viability of a biomass ECP. For example, steam or hot water cannot be transported over large distances, implying that local consumers have to be identified. In the fifth step, both inventories are combined to match the local biomass and its energy production potential (*i.e.* supply) with the local energy demand. This matchmaking process results in a variety of potential ECP designs, which are discussed in close cooperation with a sounding board. The sounding board (step 6) consists of local interested parties who are willing to make a commitment to biomass ECP development. As a result of the aforementioned discussion, in the seventh step, a conceptual design alternative is selected. This conceptual design describes the general outline of the biomass ECP. It is tailored to the local situation and defines the main processing technologies which will be used. However, based on this concept, different pre- and post-processing technologies can be adopted, resulting in different scenarios (step 8). In the ninth step, the scenarios are evaluated using an extended techno-economic evaluation tool resulting in a draft biomass ECP concept. Based on this concept, a first business plan is made in the final step and the individual roles of the participating organizations are defined. This step is crucial towards the financing of the project. If all these steps are successful, one may consider taking the final hurdles of project realization (e.g. licensing procedures, overcoming social barriers). The importance of the communication strategy throughout the entire implementation procedure may not be minimised. As B. R. Upreti and D. van der Horst (2004) conclude from the failed development of a biomass electricity plant: 'One of the important tasks in biomass energy development should be to start a constructive dialogue between all stakeholders that establishes mutual trusts and wins public support to effectively implement biomass projects'. This frequently requires feedback loops during the process as several choices are interdependent. Also note the shape of the 10-step procedure. First, the potential options are narrowed due to the adaptation to the local situation. Secondly, after a specific draft concept is chosen, this is again broadened to different scenarios. Finally, these result in one business case based on an extended techno-economic evaluation.

In conclusion: regional biomass will gain increasing importance as a renewable energy source. However, using it in a sustainable and economically feasible way is a challenging task. As a result, it is believed that the aforementioned biomass ECP-concept and 10-step procedure can provide a structured tool to facilitate the implementation process and as such contribute to the efficient and sustainable use of regionally available biomass residue streams. In this dissertation an answer will be provided to different questions within the development process.

1.3. Central research question

The aim of this dissertation is to answer the question whether biomass residue streams as a source of renewable energy and materials are interesting for investors and society and to analyze the conditions for which this is true (*i.e.* techno-economic, environmental and social). The main research question to be answered at the end of this dissertation therefore is:

What is the potential of biomass residue streams to be valorized as a source of renewable energy and materials?

In order to make this research question operational, it has been subdivided into several subquestions. Each subquestion can be placed within the general development process. An overview of the different subquestions can be found in Figure 4. This figure will also be used in the remainder of this dissertation.

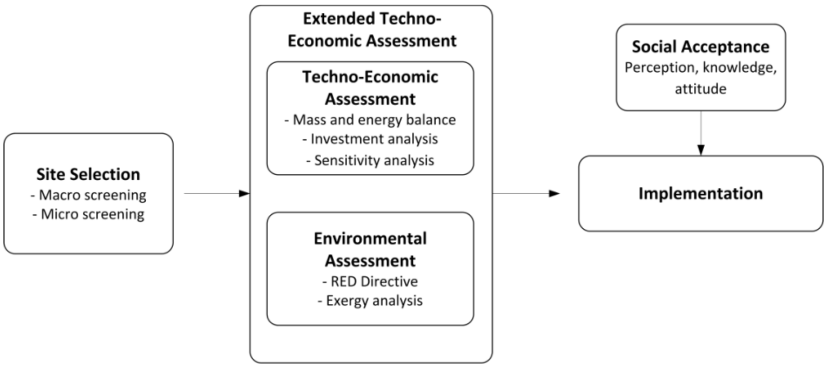

Figure 4. Overview of subquestions

1.4. Subquestions

Subquestion 1: What is a sound screening approach to determine an optimal location for regional multibiomass valorization?

In Chapter 2 an answer is provided to the question raised for a more justified site selection method. Often it is too time consuming to analyze a large region in detail and biomass site developers use one or two criteria to make a first selection within this larger area. A methodology is provided to select the potentially interesting locations using a sound screening approach based on multicriteria analysis and geographic information systems. Section 2.1 introduces the methodology. In section 2.2 the necessary details for the macro screening approach are elaborated on. The approach is applied to a case study in section 2.3. The methodology is further discussed in section 2.4.

Subquestion 2: Are energy conversion parks interesting from a techno-economic point of view?

As mentioned in the introduction, energy conversion parks are complex parks in which biomass is converted into energy and materials. After a location is selected and a concept with different scenarios for the ECP is developed (see step 1-8 in Figure 3), one should argue whether this concept is interesting from a techno-economic point of view. In Chapter 3 a methodology is developed to answer this question. Section 3.1 introduces the chapter. Section 3.2 provides more details about the developed techno-economic evaluation model. The methodology is applied to two case studies which are provided in respectively section 3.3 and section 3.4. Finally, section 3.5 holds the discussion and conclusion.

Subquestion 3: Are energy conversion parks interesting to attain the 20-20-20 EU targets?

In Chapter 4 an answer to the question whether the products produced in an ECP can be taken into account in order to attain the 20-20-20 EU targets, is provided. In section 4.1 the current discussion concerning the used evaluation procedure is introduced. Section 4.2 provides more details about the consequences of multi-pathways for the EU sustainability guidelines. In section 4.3 more information is provided on the B-SAT tool which is based on the EU sustainability guidelines, and on an alternative sustainability tool, CEENE. Differences between both methods are explained. Both methodologies are applied on a case study in section 4.4. Finally sections 4.5 discusses and concludes.

Subquestion 4: What is the knowledge, perception and attitude of biomass?

In Chapter 5 more information will be provided on the societal barriers of energy conversion parks. After a location is selected and it is proven that the developed ECP concept is interesting from a technical, economic and environmental point of view, the development process can still be hindered due to perceptual barriers. One of these barriers is the non-acceptance by the public. In Chapter 5 we will analyze the perception, knowledge and attitude towards bioenergy projects. In section 5.1 an overview is provided of accepted models that explain the relationship between perception, knowledge and attitudes and the case study is introduced. In section 5.2 more details concerning the methodology are provided. Section 5.3 holds a detailed description of the results. Finally section 5.4 further discusses and concludes the chapter.

Chapter 2.

Site Selection*

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* *Parts of this section have been published in:*
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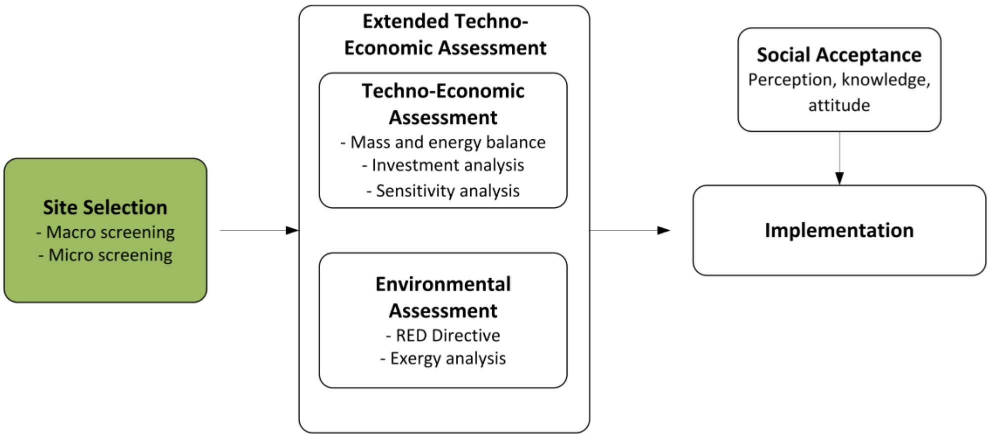
In this chapter we will provide an answer to the first sub-question, *i.e.* what is a sound screening approach to determine optimal localization for regional multibiomass valorization. This is the first step in the ECP development process.



2.1. Introduction

As indicated by Ma, Scott, DeGloria, and Lembo (2005) locating optimal sites for biomass conversion is a complex task involving many environmental, economic, and social constraints and factors. Furthermore, biomass projects are typically site-specific. Therefore, especially when a large area is considered, it is impractical and pointless to optimize for every possible plant location (Gómez, Rodrigues, Montañés, Dopazo, & Fueyo, 2010). Calvert (2011) concludes, based on an international review, that there is a lack of baseline information at the agenda-setting stage of public and private energy planning which prevents decision makers from taking bioenergy seriously. Robust information is the lubricant for decision making and is the only way to minimize the unintended consequences of those decisions. Ayoub, Martins, Wang, Seki, and Naka (2007) argue that many decision support systems (DSS) are constructed for one type of biomass from a specific point of view (economic, environmental or social).

However, understanding the interdependency of these factors is essential because the failure of one factor can lead to the failure of the whole project. A method is needed that handles multiple biomass stakeholders' objectives and involves different types of biomass. Since many stakeholders of biomass projects have diverse and often conflicting perspectives, a barrier may arise which impedes fluent communication. Therefore, an open, transparent and participatory process is needed to find a balance between the different stakeholders and to move towards a more objective method (T. Buchholz, Rametsteiner, Volk, & Luzadis, 2009). The transparency of the method is important since it builds confidence in the decision-making process where multiple stakeholders with conflicting views are involved (Starkl & Brunner, 2004). Furthermore, the participation of different stakeholders starting from the planning phase is fundamental for the smooth territorial integration of biomass projects at the local scale. Besides the complexity of biomass systems, another problem is the limited availability of data (T. Buchholz et al., 2009). Information can be generated using interviews and questionnaires with local stakeholders, but this process is time and cost consuming and hence, not feasible in a large area.

The use of multicriteria decision analysis (MCDA) is widely spread in energy planning (Løken, 2007). De Lange, Stafford, Forsyth, and Le Maitre (2012) conclude that the use of MCDA facilitates the participation process and that it has an important role in the successful uptake of policy and management strategies and long-term planning. Literature reviews by Pohekar and Ramachandran (2004) and Wang, Jing, Zhang, and Zhao (2009) showed that the analytical hierarchy process (AHP) is the most applied technique, followed by outranking techniques. Moreover, geographical information systems (GIS) are often used in the context of bioenergy (Graham, English, & Noon, 2000; Iakovou, Karagiannidis, Vlachos, Toka, & Malamakis, 2010), especially for the site selection of a biomass power plant (Ma et al., 2005; Panichelli & Gnansounou, 2008; Shi et al., 2008) and the evaluation of biomass supply (Fernandes & Costa, 2010; Fiorese & Guariso, 2010; Graham et al., 2000; Van Hoesen & Letendre, 2010; Voivontas, Assimacopoulos, & Koukios, 2001). Many authors have recognized that the combination of GIS and MCDA provides a powerful tool for site selection (Haddad & Anderson, 2008; Joerin & Musy, 2000; Ma et al., 2005). GIS offers a spatial representation of the results, whereas

MCDA takes economic, social as well as environmental aspects of the problem into account (Boggia & Cortina, 2010).

This chapter will shed its light on how to determine potential locations for biomass valorization on a regional scale within a minimum time span. Therefore, a combined MCDA-GIS approach has been developed, described as a 'macro screening'. The screening approach considers different relevant criteria to determine potential locations for biomass valorization in a specified region. In fact, a macro screening provides a first well balanced scan of the possibilities for energy production using regional biomass. The macro screening answers to most of the above mentioned concerns and is therefore considered an interesting method. It allows for policy makers and investors to be supported and motivated to study the possibilities of building energy production plants at specific locations in more detail. The approach will be discussed in detail in paragraph 2.2. In paragraph 2.3 it will be applied to a case study in Limburg, a province in the northeastern part of Belgium. In paragraph 2.4 the method's strengths and weaknesses will be discussed and the conclusions summarized. In the last paragraph of this chapter more details will be provided about the micro screening, which follows directly after the macro screening.

2.2. Methodology

The goal of the macro screening is to identify locations that are deemed 'highly interesting' for energy production based on readily available information. Often, the determination of a location is based on a single criterion (e.g. potential heat consumers or available amount of a specific type of biomass). This method is more proactive and gives an answer to policymakers and investors' demand for a more substantiated evaluation on site selection. The need for a fast and efficient way to explore the market has also been recognized in other domains such as landfill mining (van der Zee, Achterkamp, & de Visser, 2004; Van Passel et al., 2012) and sustainable agriculture (Vereijken & Hermans, 2010). Up to now this need has not been translated into an adequate methodology for biomass valorization site selection. This dissertation aims at filling this gap. A complementary approach is needed to perform a final site selection. While the macro screening significantly reduces the number of locations, the micro screening subjects the remaining locations to a more detailed exploration and determines the optimal one.

Macro screening focuses on minimizing the required time to perform site selection. It is not feasible to investigate every alternative in detail within a reasonable time frame. The macro screening consists of five steps. Firstly, all criteria on which an alternative can be rated, must be identified since site selection can be considered as a multicriteria decision making problem. Then, data must be gathered for each criterion agreed upon to be included in the analysis. These data provide a score for each alternative. Considering not every criterion is equally important, in a third step a weight must also be assigned to each criterion. Fourthly, final scores are found for every alternative by summing the multiplications of the scores and the weights per criterion. Finally, a spatial representation of the weighted criteria can be obtained by combining the MCDA method with GIS. This stepwise approach is represented in Figure 5. Note that these steps can be performed in parallel and that some steps may be repeated as a result of learning during the process. The macro screening is performed specifically for biomass site selection and therefore, takes into account the specificities typical for biomass.

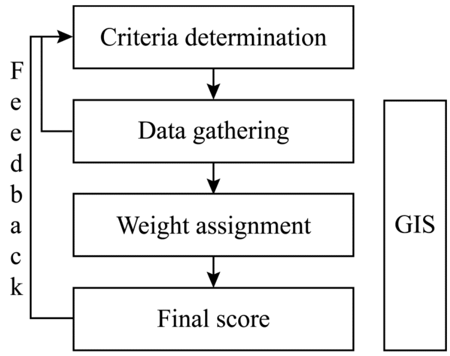


Figure 5. Macro screening approach

2.2.1. Criteria determination

To consistently assess whether a certain area is eligible for planting an installation, decision making criteria must be chosen. It is highly recommended to organize an expert panel discussion to identify a set of criteria. Experts should have different backgrounds given the value of their differing points of view (for specific recommendations in case of bioenergy projects, we refer to the next paragraph). Consequently, a maximal amount of information can be taken into account. By allowing experts to participate early on in the process, the probability of acceptance of the final decision is enhanced. Experts are preferably involved from the planning phase. The set of main criteria and their subcriteria is, however, only the starting point. During the process criteria can be added, deleted, substituted and merged in a follow-up discussion or feedback moment. At any time during the first two steps a criterion may respectively turn out to be useful, impractical, misleading or having a similar contribution as another criterion. The criteria can be quantitative as well as qualitative. An MCDA method allows for the processing of both kinds of data (Balana, Mathijs, & Muys, 2010). The criteria have to meet four requirements to be used in a macro screening: (1) comprehensibility, (2) having predictive value, (3) being operational (*i.e.* measurable and meaningful), and (4) being quantifiable based on readily available information. It is not possible to define the exact number of criteria necessary to adequately evaluate the alternatives since this is highly situation dependent. On the one hand, too little criteria lead to an incomplete answer to the problem. On the other hand, too many criteria make the processing too difficult. A formal way of knowing whether the set of criteria is sufficiently complete, other than relying on experience and intuition, does not exist. Therefore, the involvement of a significant number of experts (*i.e.* between 10 and 15 in the first step) from various backgrounds is crucial in this setting. The only rule that must be kept in mind is that the number of sublevels and the number of criteria per sublevel must be balanced for every main criterion (see *infra*, paragraph 2.2.3).

Typical for multidimensional biomass projects is the diversity of input streams and techniques. In addition, biomass projects have an influence on many factors (*i.e.* economic, social, and environmental). Therefore, it is recommended to consult local biomass experts with various fields of expertise as they are most familiar with the working situation. However, they are often only experienced with one sort of biomass and its accompanying conversion process. Hence, it is advised to invite local experts with different specific knowledge. The following list of experts is recommended to be involved when performing a macro screening for biomass projects: (1) expert(s) from the industry (e.g. wood processing, food, brewery); (2) expert(s) in forest management; (3) representative(s) of agriculture; (4) member(s) of local government; (5) expert(s) in municipal waste processing; (6) expert(s) in nature conservation and maintenance; (7) expert(s) from knowledge institutions; (8) expert(s) from similar projects; (9) private investors. The list is cross-checked with recommendations from literature (De Lange et al., 2012; Jalilova, Khadka, & Vacik, 2012; Kowalski, Stagl, Madlener, & Omann, 2009; Lahdelma, Salminen, & Hokkanen, 2000; Turcksin et al., 2011; van der Zee et al., 2004). Note that for example no expert in spatial planning is involved. The reason is that these experts are important in the next phase, *i.e.* micro screening, when more location specific details are required. Within the macro screening the geographical regions that are evaluated are too wide to take into account e.g. building prescriptions.

A set of four main criteria, recommended by the experts, was agreed upon to be sufficiently covering all important elements influencing the primary, rough location decision for a biomass project. Furthermore, it is assumed that they can answer to the need for a more uniform set of criteria for biomass projects (Ananda & Herath, 2009; T. Buchholz et al., 2009; T. S. Buchholz, Volk, & Luzadis, 2007). The four main level criteria are: 'input', 'output', 'installation' and 'society'. Input should contain the different theoretical biomass potentials. The criterion output should be composed of present heat consumers. The criterion installation should hold the biomass installations that are currently installed or planned. Finally the criterion society should measure the willingness of communities to accept the project in their area. It is interesting to take the willingness of communities into account early in the process since other cases have shown that public opposition is common (McCormick, 2010; Bishnu Raj Upreti & Dan van der Horst, 2004). Some authors even claim that the leap towards broader biomass utilization for bioenergy is more psychological than technological (Silveira, 2005). More details concerning the societal acceptance of biomass projects can be found in Chapter 5. The chosen subcriteria can differ depending on the region since a biomass project is typically site-specific and, hence, requires a unique screening (Ma et al., 2005). A list of advised subcriteria per main level is presented in the case study (see section 2.3).

2.2.2. Data gathering

The macro screening data is gathered by desk research. This data gathering is performed by the researcher and no other experts are directly involved. The data sources used must be readily available, e.g. databases, articles or public data available from research institutes, regional/national/European authorities, and internet. The researcher must always consider whether the time needed to collect the information outweighs the additional value it can provide. Since this entails many trade-offs, the found data will never give a complete representation of reality. However, this is not a necessity, the information must give an acceptable indication of reality. Yet, the more information gathered, the more likely the optimal location will be among the identified locations. After an initial set of criteria is determined, data gathering is performed in parallel to step 1.

The collected data provide a value for each criterion for every alternative. The different units, in which the criteria may be expressed, do not pose a mathematical problem because normalization can be performed. By using, for example, a linear scale transformation, a value x_{ij} will be transformed into a score r_{ij} between zero and one by using equation (1) for criteria positively influencing the goal and equation (2) for criteria negatively influencing the goal. The outcome is more favorable as r_{ij} approaches one (Freudenberg, 2003; Hwang & Yoon, 1981).

$$r_{ij} = \frac{x_{ij}}{\max_i x_{ij}} \qquad (1)$$

$$r_{ij} = \frac{\min_i x_{ij}}{x_{ij}} \quad (2)$$

2.2.3. Weight assignment

Weights have to be assigned to indicate a criterion's importance and should preferably be performed by experts (see *supra*, paragraph 2.2.1). Methods to assign weights are sensitive to changes in the number of criteria, the decision maker must therefore be certain that the set of criteria is final before going over to the weight assignment. The most popular MCDA methods are analytical hierarchy process (AHP) and outranking methods (Pohekar & Ramachandran, 2004; Wang et al., 2009).

The decision making criteria are split into several levels to form a hierarchical tree (Figure 6). Using AHP, each criterion is compared with every other criterion of the same level in their contribution to the goal in an 'm x m' pairwise comparison matrix (Figure 7). The same applies for comparing the sublevel criteria within their own branch. The value in cell a_{ij} indicates the importance of the criterion listed in the left-hand side column with respect to the criterion on the top row on a nine-point numerical scale (Table 1) (Hwang & Yoon, 1981). When a_{ij} = k, then a_{ji} = 1/k must hold for consistency reasons. Assume for example that a decision maker is perfectly consistent in weighing n objectives and let W_i be the weight that is given to objective i. This results in a pairwise comparison matrix of the following form:

$$A = \begin{bmatrix} \frac{W_1}{W_1} & \frac{W_1}{W_2} & \cdots & \frac{W_1}{W_n} \\ \frac{W_2}{W_1} & \frac{W_2}{W_2} & \cdots & \frac{W_2}{W_n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{W_n}{W_1} & \frac{W_n}{W_2} & \cdots & \frac{W_n}{W_n} \end{bmatrix}$$

Note that we do not assign two numbers W_i and W_j and as such form the ratio $\frac{W_i}{W_j}$. Instead a single number from the nine-point scale is used as indicated in Table 1, to represent the ratio. Subsequently, the weights are obtained from the matrix: firstly by summing each column, secondly by dividing every cell by its column total and finally by taking the average of each row (Balana et al., 2010; Saaty, 2008; Winston, 2003; Zopounidis & Pardalos, 2010).

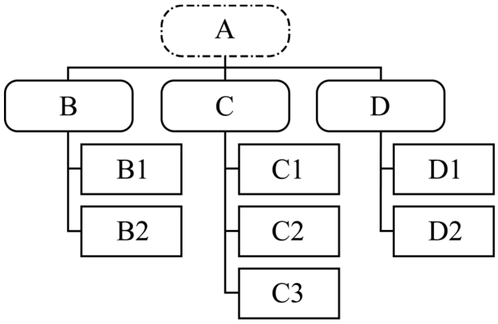


Figure 6. Hierarchical tree

RE \ CE	C1	C2	C3
C1	1	a	1/b
C2	1/a	1	c
C3	b	1/c	1

Figure 7. Pairwise comparison matrix

Table 1. Nine-point scale

1	Both criteria contribute equally to the objective
3	Moderately higher contribution to the objective of row element (RE) as compared to column element (CE)
5	Higher contribution to the objective of RE as compared to CE
7	Much higher contribution to the objective of RE as compared to CE
9	Complete dominant contribution to the objective of RE compared to CE
2, 4, 6, 8	Intermediate levels

A consistency ratio (CR) is calculated to check for inconsistency in the decision maker's comparisons. It is not ensured that decision makers are fully consistent. It is important to know how inconsistent judgments are to be able to improve the consistency if necessary. The CR of a pairwise comparison matrix is the ratio of its consistency index (CI) (*i.e.* the maximum eigenvalue (λ_{max}) of the comparison matrix, see also equation (3)) to the corresponding random index. The random index is calculated as the average of the eigenvalues of randomly generated reciprocal matrices. The CR should not exceed 0.10 for a matrix larger than '5 x 5'. Detailed calculations of the CR and CI can be found in references (Winston, 2003; Zopounidis & Pardalos, 2010) and are also provided in Appendix 1.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (3)$$

Using outranking methods, the criteria are ranked per hierarchical level. A weight w_j is assigned to each criterion depending on the rank order of the criterion using equation (4).

$$w_j = \frac{\frac{1}{k}}{\sum_{k=1}^{n} \frac{1}{k}} \quad (4)$$

Where k is the priority level or ranking of criterion j (k = 1: most important criterion; k = n: least important criterion) (Van Huylenbroeck & Damasco-Tagarino, 1998).

The weights of the main level criteria sum to one hundred and sublevel criteria's weight sum to the respective weight of their main level criterion. For example in Figure 6, the sum of the weights of the criteria B, C and D is one hundred. The weights of the sublevel criteria B1 and B2 sum to the weight of the main level criterion B. Here the rule for the number of criteria per sublevel becomes important (see *supra*, paragraph 2.2.1). Indeed, the relative share of a criterion belonging to a main criterion having lots of subcriteria is automatically lower than that of a criterion belonging to a main criterion having a similar weight but less subcriteria. Therefore, the number of subcriteria per main criterion have to be balanced, *i.e.* approximately the same number of subcriteria per main criterion.

Fischhoff, Slovic, and Lichtenstein (1980) demonstrated that the resulting weights can be influenced by the MCDA method since participants generally do not have a clear preference. As every method has its own advantages and drawbacks, it is not possible to indicate one method as being more suitable than another (Lahdelma et al., 2000; Løken, 2007). Therefore, it is recommended to use more than one MCDA method to provide comparative information and enhance the efficacy and empirical validity of the results and to select the most appropriate tool for a given problem (Ananda & Herath, 2009; T. Buchholz et al., 2009; Benjamin F. Hobbs & Horn, 1997; B.F. Hobbs & Meier, 2000; Løken, 2007; van der Zee et al., 2004; Wang et al., 2009). However, Løken (2007) concludes that it is not possible to claim that one of the MCDA methods is generally more suitable than the others. Bell, Hobbs, Elliott, Ellis, and Robinson (2000) argue that the most appropriate method depends on the set of assumptions that seems most valid for a given situation and person. In literature there is ample evidence of differences in results and recommendations between methods (Mysiak, 2006). According to Jia and Fischer (1993) the difference between methods becomes larger and more important as the number of alternatives and criteria increase. However, Benjamin F. Hobbs and Horn (1997) conclude that these disagreements or inconsistencies are inevitable and should be welcomed as an expression of the different suitability of a method for a particular situation and a decision maker.

MCDA methods take objective characteristics as well as the preferences of decision makers into account (A. Papadopoulos & Karagiannidis, 2008). Since MCDA methods are subjective, it is thus possible to direct the outcome into a certain direction. This guidance is by no means unwanted since multicriteria decision tools have been developed to assist the decision makers in efficiently and consistently formulating their true preferences (Mysiak, 2006; Stewart). The effectiveness of the approach is dependent on the interaction with the participants and the presentation of information in a way that facilitates active participation to enhance understanding, learning and discussion (De Lange et al., 2012). Also Benjamin F. Hobbs, Chankong, Hamadeh, and Stakhiv (1992) conclude that careful tutoring and close collaboration between analysts and decision makers are more important than which method is adopted. Moreover, it is important to clearly communicate the goal and the impact of the weights to the experts. To gain more insight into the resulting weights, it is interesting to have some background information on the experts.

Some typical characteristics of biomass and its conversion to energy are its complexity, site-specificity, geographic dispersion, involvement of many diverse stakeholders, and influence on different factors (Karaj, Rehl, Leis, & Müller, 2010; Shi et al., 2008; Smeets et al., 2007; Valdez-Vazquez et al., 2010; van Dam, Faaij, Lewandowski, & Fischer, 2007). These characteristics imply some specific drawbacks for using MCDA in the case of biomass applications. Due to the complexity and diversity of biomass it is difficult to define criteria such that stakeholders interpret them all in the same way. Important is the participatory development of a clear definition for every criterion with the different stakeholders or the explicit explanation to the stakeholders before starting the weighting procedure. Furthermore, the score should be carefully explained to the stakeholders. The process to come to an agreement for every criterion can be very time consuming. Therefore, it is interesting to develop a uniform list of criteria that can be used as a starting point for every biomass project. The advised set of criteria in this dissertation can be a first step to a needed uniform set of criteria for the primary screening of potential biomass conversion locations (Ananda & Herath, 2009; T. Buchholz et al., 2009; T. S. Buchholz et al., 2007). Despite the development of a uniform set of criteria, it is not possible to make a general clear-cut list that can be transferred without any adaptation to every region. Another prevalent drawback for biomass decision making is the large difference between the involved stakeholders, for example in professional knowledge, background, as well as educational level. Therefore, some stakeholders will be more confident in expressing the importance of indicators, while others will have difficulties with understanding criteria and/or methodologies. Researchers have to take this into account and find a balance among all participants (Jalilova et al., 2012). Sufficient information has to be provided to all stakeholders, without pampering those stakeholders with professional knowledge. A researcher can provide more information to those participants that have more difficulties with understanding the different criteria, however, should be careful with providing influential information. The combination of the above elements specific for biomass make it difficult to find an optimal balance between the method's complexity (*i.e.* the more criteria, the more complex for stakeholders to weigh them) and sufficient coverage of all factors influencing biomass projects (*i.e.* sufficient criteria are needed in order to catch the complexity of biomass projects).

2.2.4. Final score

By summing the multiplication of the scores (step 2, performed by the researcher) with the weights (step 3, performed by the experts) per criterion, a final score for every alternative is obtained. This method is based on the weighted sum method (WSM) (Wang et al., 2009), a simple and user-friendly approach to identify the most preferred alternative (Hwang & Yoon, 1981; Løken, 2007). The higher the final score, the more interesting an option is. Another method to get a final ranking may be used as well. The resulting rank order merely gives an indication of the most interesting options.

The advantage of using MCDA methods is that it makes the decision making process traceable and transparent. Based on a GIS visualization (see *infra*, paragraph 2.2.5) the decision maker can show why some decisions were made that are slightly differing from the final rank order obtained via the method. In the end it is the decision maker that makes the final decision. It is for example recommended that the neighboring areas are taken into account as well. On the one hand to check for serendipitous synergies, on the other hand to look for areas that are less attractive due to their low-scoring surrounding areas. After obtaining the final scores, the decision maker can reflect on the results. Criteria can be deleted or added, however, in either case the process should be started again from the beginning bearing in mind the sensitivity of weight assignment methods for changes in criteria (see *supra*, paragraph 2.2.3).

2.2.5. Spatial representation

For biomass projects, the use of MCDA alone is not sufficient to take into account the geographic dispersion of biomass and the different geographical levels. A geographical information system (GIS), *i.e.* the software and hardware needed to display geographical data in a mapped format (Graham et al., 2000), can be applied to the model's output for a better grasp on the geographical context. Furthermore, GIS allows for better data management on a spatial level (Boggia & Cortina, 2010). There are many geographical levels (e.g. province, community, address) on which information can be found. The geographical level is dependent on the way results are represented: numerically or spatially. Information can be numerically ranked (*i.e.* solely based on the total score, the result of steps 1-4), which implies grouping on a common geographical level. However, some criteria can be valued on a more detailed level than others. For the use of MCDA one should always aggregate the information to the highest common level (*i.e.* least detailed) on which data is available for reasons of comparison. A coupling or integration with GIS is necessary, especially for biomass projects, to comprehensibly present data and/or results and visualize the data simultaneously on the detailed levels (Zubaryeva, Zaccarelli, Del Giudice, & Zurlini, 2012) (adding step 5). This more detailed representation allows for taking into account a more precise region during the micro screening.

2.3. Case study - Limburg

It is chosen to apply the methodology to the case of Limburg, a province in the northeastern part of Belgium. This area has a total surface of 2,422 km² and is divided into forty four communities with a rather high population density. It is a province with a lot of forests compared to other Flemish provinces, where renewable energy initiatives receive a lot of attention from different stakeholders (investors, policy, society, academics, …). Several projects are ongoing, such as a provincial project that strives towards a CO_2 neutral Limburg by 2020. The above mentioned macro screening method is applied to identify the most promising communities in the province to install a multidimensional biomass project (*i.e.* ECP).

2.3.1. Criteria determination

In the first step experts were identified to determine the useful criteria for regional, multidimensional biomass projects. In total ten experts were consulted, all with different professional backgrounds. A meeting was organized to stimulate the experts in expressing their points of view after which the most important criteria were deducted. Based on our experience it can be advised to involve between 10 and 15 experts in this step. We performed the analysis for multibiomass concepts. By involving 10 to 15 experts all different backgrounds concerning biomass are taken into account. As defined in paragraph 2.2.1, four main criteria were identified. Each criterion consists of a number of subcriteria (see Figure 8). The subcriteria used to estimate the amount of biomass input are selected as such that they do not compete with food, feed or other high value applications. Generally spoken one can take into account residues from industry, agriculture, forests, communities and nature. The specific residues are dependent on climate and soil characteristics and hence differ for every region. However, since the residues from agriculture are for example scored as the total amount of hectares dedicated to agriculture, this criterion can be used in every region (see *infra*, paragraph 2.3.2). Experts agreed that it was not interesting to break the criteria down for every type of agricultural crop since this would make the weight assignment too complex. The subcriteria for 'Society' are the most difficult to advise a uniform list for, since these are highly situation dependent. Moreover, it is not possible to recommend an aggregated level that allows for sufficient detail. Furthermore, it is advised based on our experience to take no more than four main criteria and maximum six subcriteria per main level criterion. When taking into account more criteria, the weighting procedure becomes very complex and would take too long for the participants. In our study a meeting of two hours to weight all the criteria was already required.

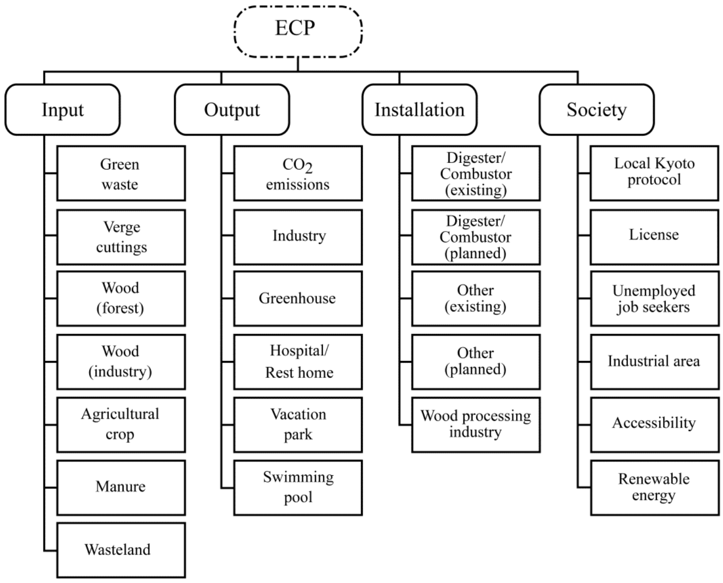


Figure 8. Selected criteria based on expert knowledge

2.3.2. Data gathering

In the next step information was gathered by the researcher for each of the criteria using desk research. The exact measure used for each of the criteria is given in Table 2. 'Input' contains the biomass potentials. Different types of potential exist: theoretical, technical, economic, sustainable, … (Karaj et al., 2010). In this study the theoretical potential, *i.e.* the overall maximum amount of biomass which can be considered theoretically available within fundamental bio-physical limits (Smeets et al., 2007), is used since the macro screening focuses on minimizing the time needed. It is however important to keep this difference in mind. In many situations the economic potential is of interest. In the micro screening the restrictions needed to find the economic or even the sustainable potentials should be provided. In order to gather these restrictions, one has to perform questionnaires and/or interviews. Considering the large area that is under revision for interviewing, it is necessary to narrow the scope first. To that end the macro screening is a very useful tool. Note that for the sub-criterion 'wood (forest)' for instance the total area of forestry is taken into account. Consequently, it may seem that wood is taken into account that could be used for furniture, particleboard, *etc.* However, on a macro-level a proxy could just as well have been used to estimate the amount of wood residues. For example, we could have used 0.48-2.64 ton/ha/year of woody residues (Dagnelie, R. Palm, J. Rondeux, & Thill, 1985; Zianis, Muukkonen, Mäkipää, & Mencuccini, 2005) of which a minimum of 45% should stay within the forest for ecological concerns (Briedis, Wilson, Benjamin, & Wagner, 2011). However, mathematically no difference in the final score will be noticeable, since the final score is normalized (see *supra*, paragraph 2.2.2) and thus that level of detail is lost. Still, since the macro screening is traceable it can be interesting to integrate this proxy and go back to it afterwards. 'Output' contains the current heat consumers, 'Installation' holds the biomass installations that are currently installed or planned and the criterion 'society' measures the willingness of communities to accept the project in their area.

Table 2. Criteria measures

Input			
Green Waste [1]	Vegetable, fruit and garden waste (ton)	Agricultural crops [8]	Total area dedicated to agricultural crops (ha)
Verge Cuttings [2,3,4]	Verge cuttings (ton)	Manure [8,9]	Manure from pork, cattle and chicken (ton)
Wood (forest) [5,6]	Total area of forestry (ha)	Wasteland [8]	Total area of wasteland (ha)
Wood (industry) [7]	Total amount of carpentries (#)		
Output			
CO_2-emissions[10]	Total amount of CO_2 allowances (ton CO_2)	Hospitals/Resthomes[12,13]	Total amount of beds in hospitals and rest homes (#)
Industry[11]	Total amount of breweries, food industry, furniture industry, drying (#)	Vacation parks[14]	Total amount of cottages (#)
Greenhouses[8]	Total area dedicated to greenhouses (ha)	Swimming pools[15]	Total amount of indoor, heated outdoor and subtropical pools (#)

Installation			
Digester/combustor (existing)[16]	Installed power from digesters and combustors (kW)	Other (planned)[17]	Total amount of planned bio oil, biosteam, compost and torrefaction installations
Digester/combustor (planned)[16]	Planned power from digesters and combustors (kW)	Wood processing industry[7,11]	Total amount of carpentries (#)
Other (existing)[17]	Total amount of existing bio oil, biosteam, compost and torrefaction installations		
Society			
Local Kyoto protocol[18]	Community acknowledgment of the local Kyoto protocol (yes-no)	Industrial area[11]	Total area of free industrial area (ha)
License[16]	Total number of licenses granted for biomass-to-energy conversion installations (#)	Accessibility[2,4]	Total amount of motorways and waterways (km)
Unemployed job seekers[19]	Total amount of unemployed job seekers (#)	Renewable energy[16]	Total amount of installed power from renewable energy sources (sun, wind and biomass)

Sources:
1 www.limburg.net
2 FOD economie 'lengte van het wegennet'
3 CMK Uhasselt
4 NV De Scheepvaart
5 AGIV
6 www.bosgroepen.be
7 www.handelsgids.be
8 FOD economie 'landbouwenquête'
9 MIRA
10 www.lne.be
11 POM limburg
12 website hospitals
13 www.derusthuizen.be
14 www.toerismelimburg.be
15 http://zwembad.injebuurt.be/injebuurt/city/Limburg
16 VREG
17 website installation
18 Bond Beter Leefmilieu
19 VDAB

2.3.3. Weight assignment

A new expert meeting with twenty-five participants was organized to agree upon the importance of every criterion shown in Figure 8. Within the experts, two different groups can be distinguished: (1) the project group consisting of project partners, and (2) the sounding board composed of stakeholders who are currently active in related activities (see *supra*, paragraph 2.2.1). The first group was also used earlier in step 1 (see paragraph 2.3.1) to determine the relevant criteria. The same criteria were presented to all experts to assign weights, representing their opinions and preferences. Every expert received an equal weight because their viewpoint was considered equally important. There was no correction for outliers since there was no reason to consider the opinion of an expert as being wrong. Biomass is a complex concept that can contain different types of biomass and different conversion processes. Depending on the background and specific interest of the different experts, some might argue that other criteria are more important. For example an expert active in wood processing technologies might argue that the proximity of wood processing industry is most important whereas this might not be true for an expert active in the processing of wet biomass streams. From every expert some background information was gathered by asking supplementary questions at the end of the weight assignment. They were asked which country they are living in, what their field of expertise is, which sector they are working in, which function they have and which biomass type is most related to their activities. In Table 3 the total number of experts per background criterion is summarized. This information will be used to check whether an expert’s background has an influence on the assigned weights.

In this work the weights are first obtained using the AHP method. Table 4 summarizes the geometric mean of the weight per criterion, as recommended by Forman and Peniwati (1998). To check the robustness of these weights, they are compared with the weights obtained by direct weighting and ranking. The rank correlations (kendall’s tau) were calculated in order to evaluate the degree of similarity between the sets of ranks. The Kendall’s rank correlation compares the ordering of the samples and assigns a value of 1 or 0 to the pairs when its order corresponds or not to the way the objects were ordered. For more information on the specific calculations the work of Abdi (2007) can be consulted. In our test the kendall’s tau are all positive and significant as shown in Table 5. This means that the rank order of the weights does not differ much between the methods.

Table 3. Total number of experts per background criterion

Criterion	Sub criterion	# experts
Group	Project group	8
	Sounding board	17
Country	Belgium	20
	The Netherlands	5
Expertise*	Biological	5
	Chemical	3
	Economic	5
	Technological	9
Sector	Industry	4
	Environment/Nature	6
	Academic	10
	Government	5
Function	Public servant	6
	Docent	4
	Researcher	8
	Project manager	7
Biomass	Wood	6
	General	12
	No affinity	7

* missing data

Table 4. Geometric mean weight per criterion via AHP

Criterion	AHP
Input	41,33%
Output	27,86%
Installation	17,11%
Society	13,70%
Green waste	10,98%
Verge cuttings	8,57%
Wood (forest)	6,21%
Wood (industry)	4,67%
Agricultural crop	4,14%
Manure	3,52%
Wasteland	3,25%

CO_2 emissions	2,93%
Industry	7,65%
Greenhouse	6,67%
Hospital/Rest home	4,11%
Vacation park	2,97%
Swimming pool	3,52%
Local Kyoto protocol	1,15%
License	1,48%
Unemployed job seekers	0,76%
Industrial area	3,42%
Accessibility	4,87%
Renewable energy	2,02%
Digester/Combustor (existing)	4,36%
Digester/Combustor (planned)	3,31%
Other (existing)	3,92%
Other (planned)	3,07%
Wood processing industry	2,44%

Table 5. Kendall's tau rank correlation

Kendall's tau_b	**AHP**	**Direct**	**Ranking**
AHP	1	0.949**	0.943**
Direct		1	0.960**
Ranking			1

** 0.01

To see whether the expert's background has an influence on the assigned weights, a Kruskal-Wallis test is performed. The Kruskal-Wallis test is a nonparametric test for comparing several independent random samples. It is an alternative for the one-way ANOVA test. The null hypothesis says that all distribution functions are equal. The alternative hypothesis states that at least one of the populations tends to yield larger values than minimally one of the others. Note that the test cannot tell which specific groups are statistically different from each other. In order to do so posthoc tests are needed. The results are summarized in Table 6. The type of biomass that is most related to the expert's activities has an influence on most weights. The Kruskal-Wallis test indicates a difference for four criteria out of twenty eight or 14% of the criteria, which is a rather small percentage. It may be concluded that in the case study the background of the experts has a negligible influence.

The expert meeting to assign weights to the criteria was mainly composed of different experts compared to the ones determining the criteria. During the second expert meeting some concern was expressed because some sounding board members did not completely agree with the criteria or their definition. It is therefore important to stimulate the experts to fully share their opinions while providing sufficient answers to their questions. The results show that the group to which an expert belonged, had an influence on solely three criteria.

Table 6. Influence of experts' background on the number of criteria affected

Background	**AHP**	
	#	%
Country	2	7
Group	3	11
Function	3	11
Biomass	4	14
Expertise	2	7
Sector	2	7

Total: 28 criteria

2.3.4. Final score

Combining the scores, obtained by the researcher from step 2, with the weights, obtained by the experts in step 3, resulted in one final score for every community, seeing that all scores were allocated to this common geographic level. Note that the final scores are found for every alternative by summing the multiplications of the scores and the weights per criterion. Now, the communities can be ranked and demonstrated visually (see Figure 9). The darker the area, the more interesting communities are to plant a multidimensional biomass project. The top five communities with the highest score are Genk, Sint-Truiden, Houthalen-Helchteren, Lommel and Bilzen. As mentioned in section 2.4, the decision maker makes the final decision which can differ slightly from the final ranking. The macro screening gives an indication of the most interesting locations, but cannot indicate the most preferred one. Once a decision has been taken, the method helps to create a supportive policy framework.

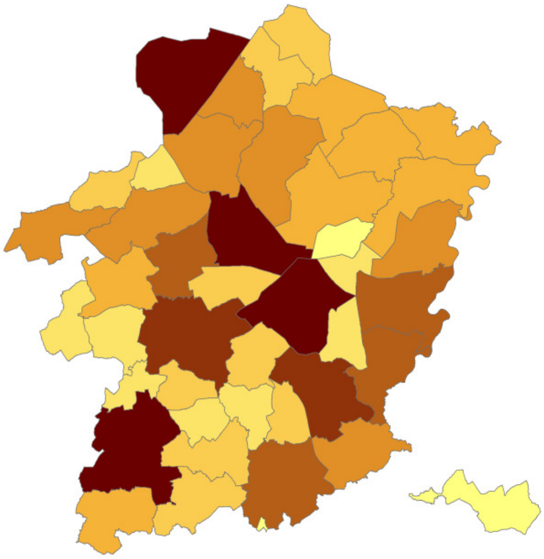


Figure 9. Spatial representation of final score per community

2.3.5. Spatial representation

However, for site selection it is interesting to take the different geographic levels into account and combine them for an integrated representation of the results. Given that this is hard to achieve numerically, the weighted criteria should be presented using GIS (Figure 10). GIS allows the user to display the results using raster data with a cell size of 500 m x 500 m. This way, it is possible to determine the regions, even within communities, which are particularly suitable for biomass conversion facilities. For all subcriteria in the criteria 'Input' and 'Society' it was chosen to use the level of communities (*i.e.* cfr. paragraph 2.3.4). Since heat cannot be transported over a large distance, it is valuable to use the exact location of all potential heat customers in the 'Output' criterion.

The same applies for the 'Installation' criterion. Extending a current installation or combining multiple techniques can only be done at that particular location, so only the score of that location (cell) is elevated. The final score for every cell is determined in the same way (*i.e.* the multiplication of the score and the weight per criterion). Note that the scores for 'Input' and 'Society' or added on a community level and that the specific scores for 'Output' and 'Installation' are added for the respective cells that contain the location of a heat consumer or installation. Figure 10 shows the added value of using MCDA in combination with GIS. The color scale consists of the weighted scores for the different criteria. The darker the color of a location, the higher the score and the more interesting that location will be for biomass conversion projects.

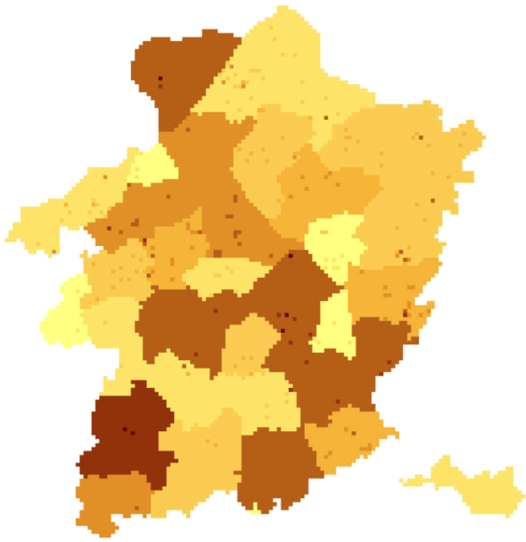


Figure 10. Spatial representation of weighted criteria

2.3.6. Valorization of results

In this study it was chosen to apply the multi-attribute value theory (MAVT) method to get a final ranking of the communities. The criteria were first provided a score, second a weight was provided to the different criteria and finally a rank of the communities was made based on the final score (*i.e.* sum of the multiplication of the scores with the weights per criterion). To check for robustness, the elimination and choice expressing reality (ELECTRE) method was applied, which is based on pairwise comparisons. The method examines the degree to which the preference weights are in agreement with pairwise dominance relationships, as well as the degree to which weighted evaluations differ from each other (Hwang & Yoon, 1981). With the ELECTRE method an exact ranking cannot be determined as with the MAVT method because lots of comparisons are undecided. However, the most dominant communities can be indicated and it can be concluded that the same communities are indicated as most interesting. Figure 11 gives an overview of the eleven communities that are indicated as most dominant (*i.e.* the community dominates (indicated by an arrow in Figure 11) at least twenty two other communities) by ELECTRE. Within this top ranking Beringen, Maasmechelen en Gingelom are eliminated because these are dominated by the other most dominant communities (red). Tongeren (orange) is dominated by Sint-Truiden and therefore is less interesting. Sint-Truiden and Lanaken (orange) are both dominated by Bocholt (*i.e.* a community that only dominates fifteen communities and therefore is not represented in the figure) and as a result are also less interesting. The green communities dominate other communities but are themselves not dominated and consequently are among the most interesting locations. Lommel (blue) dominates none of the other communities, but is not dominated itself and hence is also a potential candidate for further investigation.

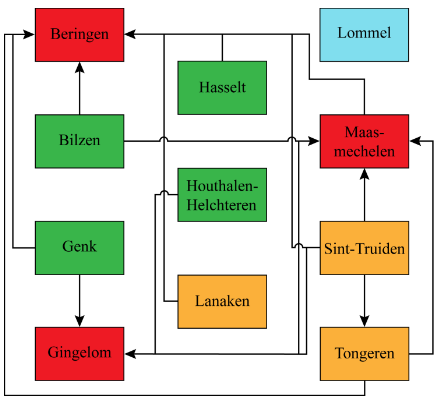


Figure 11. Top rank communities indicated by ELECTRE

2.4. Discussion and conclusion

A macro screening approach was developed and used to determine the most interesting locations for the Limburg province within a minimal time span. Starting with an expert meeting to determine the appropriate criteria is important to gain their support from the beginning. The weights, assigned via an AHP method, must also be determined by experts. By assigning weights, experts can guide the outcome into a certain direction. This guidance is valuable since it can generate insight into their different viewpoints. The final score is obtained by using a simple and traceable MAVT–based method. In the last phase GIS is used to arrive at a clear, visual representation of the different weighted criteria. GIS allows for an integration on different geographic levels to obtain a more detailed representation of the results. The macro screening only gives an indication of the potentially interesting locations and cannot select the best location among the alternatives. Therefore, it cannot stand alone as a decision tool and should be succeeded by a thorough investigation of the best-scoring locations. The macro screening approach is a supportive and motivational tool to utilize as input for the micro screening to support and motivate partners, investors, policy makers, … that allows for studying the possibilities of building biomass conversion plants at specific locations. The micro screening will take into account the economic biomass potential within a chosen region. Stakeholder interviews have to be done to identify the interest to participate in the project. Also the transport situation and economic parameters have to be integrated. The case study has shown that it was possible to drastically reduce the potential locations to place a multidimensional biomass project to the most interesting ones using a macro screening. It can therefore be concluded that the macro screening method provides a fast and efficient way to explore the market for biomass valorization site selection. Moreover the method is generic, so it can be applied to other domains, such as other renewable energy projects (sun, wind, …) or for example site selection for schools, nursing homes, hospitals or industry. Furthermore, it would be interesting to apply the methodology in another region with its own characteristics such as other specific biomass characteristics, legal environment and economic situation.

In the following some recommendations for further research are given. Firstly some criteria are rather ambiguous and can be seen as benefit criteria (synergy) or as cost criteria (competition). This distinction has an influence on the equations to use in the normalization step. In this study 'Installation' is an example of such a criterion. The criterion and its subcriteria are considered as benefit criteria in the model since the major part of the experts indicated them as such. However, Table 7 shows that the opinion of the experts were not that unanimous for all criteria. An additional expert discussion could provide some clarity.

Table 7. Synergy versus competition

Criterion	Synergy	Competition
Digester/Combustor (existing)*	14	9
Digester/Combustor (planned)*	13	10
Other (existing)*	16	6
Other (planned)*	18	4
Wood processing industry*	19	2

* missing data

Secondly the case study indicated that the differences in attributed weight between the project group and the sounding board were only significant in 11% of the criteria. During the second meeting some concern was expressed about the selected criteria, but the fact that the criteria were determined by other experts seemed comforting. Further research should be performed to prove whether this comforting feeling is really a result of the knowledge that the criteria were determined by experts or that it is sufficient to determine the criteria ourselves and to provide the experts with sufficient information about the choice and definition of criteria. One can ask oneself what the actual influence of weighing is. In the case study the weights only have a limited impact on the top ten ranked communities. If our goal was to solely indicate those communities that have the most potential, the same weight (or even no weight) could have been assigned to all criteria. Nevertheless, the weights give an insight in the importance experts attach to criteria and thus indicate how experts would make their choice if no macro screening was used. The weights do have an impact on the middle ranked communities. Hence, one of the advantages of using GIS is that neighboring communities can be taken into account when making the final decision. Since neighboring communities may be middle ranked, it is very interesting to assign weights when using GIS. Note that in other studies the weights can have an influence on all alternatives.

Thirdly, in the case study an expert's background does not have an influence on the assigned weights. Further research should indicate whether there are other variables that do have an impact on the resulting weights.

Finally, in some cases it can be desirable to exclude a location when the score on one criterion is unacceptably low or even nonexistent. In other words, the low score for that criterion cannot be compensated by a high score for another criterion. In our case study a compensatory methodology is applied in which disadvantages can be offset by an advantage on another criterion. In short, a compensatory methodology allows to get a sound measure of the overall performance of a location whereas a non-compensatory methodology alerts decision-makers for the presence of a particularly poor performance with respect to an individual criteria (Jeffreys, 2004). So, if the researcher wants that no compensation is allowed and thus that a high score on a criterion cannot compensate a lower score on another criterion, it can be opted to use non-compensatory evaluation tools. However, the researcher should keep in mind that this choice restricts the extent to which the overall preferences between options can be established. One type of a non-compensatory methodology is the dominance model which is based on a series of yes/no calculations.

The micro screening follows directly after the macro screening and is not a step of the macro screening itself. The locations marked as 'highly interesting' in the macro screening should be investigated in more detail, described as a micro screening. Relevant agencies, investors, partners,… are contacted personally and the needed information is gathered through questionnaires and interviews. In fact, a macro screening provides the information (and motivation) for investors and policy makers where to perform a micro screening.

Chapter 3.

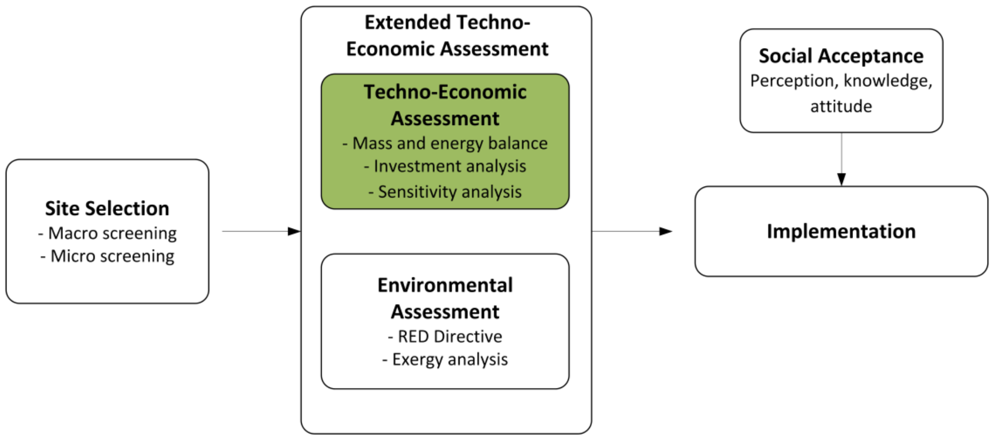
Techno-Economic Assessment*

* *Parts of this section have been published in:*
Van Dael, M., Kuppens, T., Lizin, S., and Van Passel, S. (2014) Techno-economic assessment methodology for ultrasonic production of biofuels In: Fang, Z., Smith, R.L., Qi, X. (editors), production of biofuels and chemicals: ultrasound, Springer Book Series – Biofuels and Biorefineries 4. DOI 10.1007/978-94-017-9624-8_12.

Van Dael, M., Márquez, N., Reumerman, P., Pelkmans, L., Kuppens, T., and Van Passel, S. (2014) Development and techno-economic evaluation of a biorefinery based on biomass (waste) streams – case study in the Netherlands. Biofuels, Bioprod. Bioref. 8, p. 635-644 doi: 10.1002/bbb.1460.

Van Dael, M., Van Passel, S., Pelkmans, L., Guisson, R., Reumerman, P., Marquez-Luzardo, N., Witters, N., and Broeze, J. (2013) A techno-economic evaluation of a biomass energy conversion park. Applied Energy 104(0), p. 611-622.

As seen in the previous chapter, for the development of a biomass ECP, a macro screening is used first to determine potential interesting locations. Secondly, available regional biomass residue types are inventoried and the most important stakeholders such as suppliers of biomass, investors, government, and heat customers are consulted. This stakeholder participation contributes to the likelihood of acceptance and eventual realization of the concepts. More details on the importance of local support is provided in Chapter 5. Finally, each design has to be evaluated: technically, economically as well as environmentally. The different unidimensional processes of the concept are evaluated separately. Afterwards, the biomass ECP is assessed and synergies are identified. In this and the following chapter the methodology used to assess the feasibility of the different concepts will be further elaborated. The extended techno-economic assessment (TEA) model is provided and applied on two case studies. The aim is (i) to identify the technical and economic advantages of combining conversion technologies primarily based on regional residue streams into a multidimensional plant compared to the separate use of the different conversion technologies and (ii) to identify the main drivers of profitability. In the next chapter, the environmental assessment, which is part of the extended TEA, is provided.



3.1. Introduction

When developing innovative technologies, it is important to have a clear idea on the economic performance of the technology or the process. Proving economic viability will increase private companies' interest. It is also important to know which parameters one should focus on during the development of the technology or the process. A parameter which only has a minor influence on the economic performance of the whole process may not be worth the effort of further improvement. Furthermore, for the evaluation of ECP concepts a method is needed that allows for a uniform analysis. At the moment a systematic economic analysis tool that integrates both technical and economic calculations is lacking. Often the economic calculations are added ex-post to get a first idea of the economic feasibility of developed concepts. However, detailed information on the used parameters is in many cases not provided. Moreover, an insight in the parameters which influence the economic feasibility is most often not given. Models that do provide this kind of analysis are in many cases not integrated with the technical calculations. This implies that it cannot be determined whether technical or economic parameters are most important for the economic feasibility. This also causes researchers to have to perform a technical optimization first, followed by an economic optimization. As a consequence, researchers cannot determine which technical parameters they should focus on in order to enhance the chances of actual implementation. Therefore, the likely possibility exists that technical optimizations are executed on parameters that have a negligible influence on the economic feasibility. As such, R&D costs can become substantial. Moreover, by doing so, no evaluation is made yet of the sustainability of the process. However, in case of bioenergy in Europe this is important since subsidies are best provided to technologies that allow for producing energy products that may be taken into account for attaining the 20-20-20 EU targets. Therefore, the use of techno-economic assessment (TEA) tools can help in solving this problem. A techno-economic assessment, also called techno-economic evaluation or techno-economic analysis, is a rather new term which is more frequently used since 2010. A search was performed on EBSCOHOST to check how many scientific papers mention 'techno-economic assessment', 'techno-economic analysis' or 'techno-economic evaluation' in the title since 1995. The results of this search are provided in Figure 12. The number of papers that mention one of the three terms in the text is almost double the number of papers which mention the term in the title as well. Furthermore, it is found that almost half of the papers that mention TEA or one of the other synonyms can be linked to biomass.

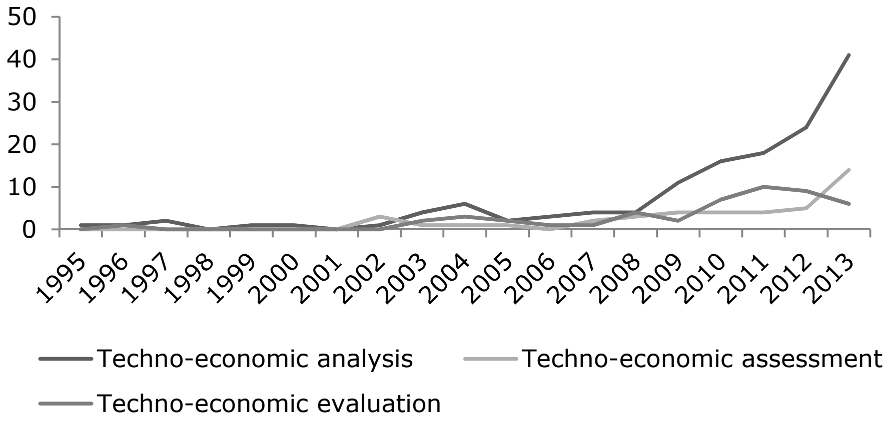


Figure 12. Number of papers mentioning TEA in title (EBSCOHOST)

Although the use of techno-economic assessments is significantly increasing, no clear accepted definition exists of what constitutes a TEA. However, some efforts have been made to provide a definition of the TEA methodology. Kantor et al. (2010) describe TEA as an analysis that integrates investment analysis with a performance analysis that takes into account some technical calculations. Smura, Kiiski, and Hämmäinen (2007) provide the following definition: "Techno-economic modeling methods are typically used to evaluate the economic feasibility of new technologies and services. Techno-economic modeling combines forecasting, […], and investment analysis methods, typically utilizing spreadsheet-based tool". The National Advance Biofuels Consortium of the United States describes the goal of TEA as follows: "TEA combines process modeling and engineering design with economic evaluation to qualitatively understand the impact that technology and research breakthroughs have on the financial viability of a conversion strategy" (NABC, 2011). However, in this chapter, we will use the definition provided by T. Kuppens (2012) in which a TEA is defined as '*the evaluation of the technic performance or potential and the economic feasibility of a new technology that aims to improve the social or environmental impact of a technology currently in practice, and which helps decision makers in directing research and development or investments.'*.

According to T. Kuppens (2012) a TEA has to answer three important questions: (1) How does the technology work? (2) Is the technology profitable? and (3) Is the technology desirable? However, in this dissertation, a TEA consists of an integrated technological (*i.e.* mass and energy balance) and economic evaluation (*i.e.* investment analysis) only. Adding a sustainability analysis (*i.e.* answering the third question) can be seen as an extended form of a TEA. In short, TEA can help to optimize the development of a process and to determine the most important parameters. Consistently applying the methodology will enhance chances of success when introducing (innovative) processes on the market. For that reason, the development process will be divided in different steps or stages after which a go/no-go decision has to be taken. The TEA can help in taking this decision and as such diminishes chances of missed opportunities or failed market introductions. Focus needs to be lying on the dynamics of a TEA and the integration of technical (e.g. mass and energy balance) and economic calculations. Too often both calculations are done separately which keeps researchers from identifying the technical parameters that have the highest impact on the economic performance. Although researchers may have a good idea of these parameters, when applying a dynamic TEA it can help to convince potential investors of the success of the technology, especially since TEA allows for risk analysis that is essential when dealing with innovative technologies.

A TEA can be applied to both a project that is still in its development-stage (ex-ante) and to one that has been already implemented and is either expanding or re-evaluating its conditions (ex-post). It is nevertheless advised to perform a TEA from the early development of innovative processes. In that case, a TEA can provide: (1) an initial assessment on the overall technical and operational barriers to overcome, (2) an optimal sizing for the project in terms of feedstock availability or plant capacity, (3) desirable product yields and waste management and (4) an indication of the (preliminary) economic feasibility or the main technical or financial factors that limit its feasibility. Furthermore, one should keep in mind that finding data for evaluating projects, costs a lot of time and money. Searching for this kind of information concerning parameters that do not have a large impact on the economic feasibility might be a waste of resources. Furthermore, a broader market study needs to be done to be sure that the process' end products do have market potential. Also, it should be investigated whether all input streams are available on the market and under which conditions. Input streams might for example not be available in the amount needed, they might be or become expensive when solutions are found for the stream, or they might be polluted requiring additional treatments (and costs) that need to be integrated. Often in development stages homogeneous systems are used for testing and for the resulting economic analysis. However, in reality such input streams are often unavailable, causing additional costs to be incurred. Alternatively, it might be that the research does not have sufficient potential.

Although a definition is provided by T. Kuppens (2012), clear methodological guidelines are still lacking. There are even no textbooks on TEA, unlike cost-benefit analysis (CBA). On top, as mentioned in the introduction, many scholars incorrectly call their analysis a techno-economic analysis whereas they perform a technical and an economic analysis separately. Therefore, in the following, some recommendations will be provided on how to perform a TEA for biomass projects based on the techno-economic spreadsheet model (Microsoft Excel©) which is developed in the course of this dissertation.

3.2. Methodology

A TEA can be divided into four different phases. As information gathering is expensive, a TEA is performed in an iterative way with a go/no-go decision after every iteration. First, a market study is performed. Second, a preliminary process design is defined and translated into a simplified process flow diagram and mass and energy balance. Third, this information is directly integrated into a dynamic CBA (*i.e.* economic evaluation). From this analysis, the profitability is identified. Fourth, a risk analysis is performed to identify the potential barriers. Optionally, an environmental analysis can be added as a fifth phase to produce an extended TEA. Note that both technological, as well as economic barriers can be identified thanks to the direct integration. Based on the results of this cycle, risk reduction strategies can be formulated and steps can be repeated when the results sound promising. These four phases are also mentioned by Verbrugge, Casier, Van Ooteghem, and Lannoo (2008) and Barbiroli (1997). A schematic overview of the TEA phases can be found in Figure 13.

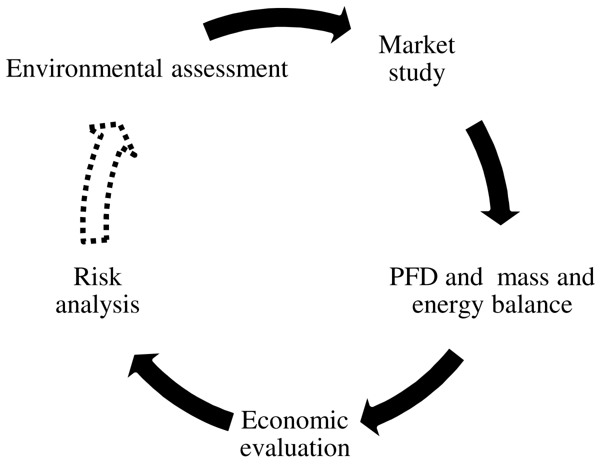


Figure 13. Schematic overview of (extended) TEA methodology

The extended TEA methodology can be framed within the wider concept of sustainability assessment tools. In general, a sustainability assessment should integrate economic, environmental as well as social aspects. However, many scholars focus on only one dimension of sustainability. This so called reductionism is compatible with the question raised by stakeholders and policy makers to keep it simple. Furthermore, according to Alexandros Gasparatos, El-Haram, and Horner (2008) the different reductionist methodologies and tools can produce a wealth of information and provide significant insights to the Sustainable Development debate. Following A. Gasparatos and Scolobig (2012) sustainability assessment tools can be divided into three main categories: (1) monetary tools, (2) biophysical tools, and (3) indicator tools. The different tools differ in their assumptions about what is important to be measured, how to measure it, who and in what role needs to be considered in the assessment, and what sustainability perspectives are both relevant and legitimate. The authors conclude that a combination of different tools might be more appropriate to represent sustainability than using a single tool (*i.e.* reductionism). An extended TEA is an example of such a combination of monetary tools and biophysical tools. Still, the challenge remains to integrate the different assessment tools and to synthesize the output, as indicated by A. Gasparatos and Scolobig (2012).

The TEA model/tool is preferably excel-based as many innovative processes are not yet integrated into existing software packages. On top, using existing software packages often requires dedicated training. Furthermore, an advanced level of knowledge is needed to change the assumptions made within packages. Excel-based tools enhance user friendliness and transparency, as most scientists are familiar with working in Excel. Also, it allows designing a model that is very specific to the researcher’s process and allows for an increasing level of detail throughout the different TEA iterations.

The Excel-based model consists of two data input sheets, one with data regarding the mass and energy balance and one with information concerning the economic parameters. Consequently, both the second and third phase are directly integrated in the model. The first phase (*i.e.* market study) is used to define the broader scope of the technology development and to gather data that will be used as input in the other phases. The fourth phase (*i.e.* risk analysis) can be performed on the integrated model in Excel. Especially for this last phase it is interesting to use input sheets since this allows the quick selection of the parameters that have to be varied in this analysis. Furthermore, the model contains one output sheet for every concept that is evaluated. In other words, different alternative processes can be gathered in one model, which is interesting for comparison afterwards. The sheet that is provided for every alternative, consists of a process flow diagram (PFD) of the concept, the mass and energy balance calculations and a cost benefit analysis (CBA) with calculation of the most frequently used investment criteria, *i.e.* net present value (NPV), internal rate of return (IRR) and discounted payback period (DPBP) (Biezma & Cristóbal, 2006; Carpaneto, Chicco, Mancarella, & Russo, 2011; Karellas, Boukis, & Kontopoulos, 2010; Levy & Sarnat, 1994; Lorie & Savage, 1955). In the technical analysis part a PFD is generated per ECP design. This diagram describes the ECP inputs and outputs and the material and energy flows between individual processes. Using Material Flow Analysis (MFA) modeling, the mass and energy balances are calculated for each concept, including mutual exchanges and synergies between the individual concepts. Outcomes of the analyses include:

- A quantification of the synergies such as increase in resource valorization and reduction of energy and water need through mutual connections and reduction of waste;
- The properties of residues per individual process and an evaluation of suitability as input for other processes;
- An evaluation of the technical feasibility of the proposed connections.

As already mentioned, in a first iteration not all technical, nor economic details are taken into account in the model. It takes too much time and effort to make a detailed analysis from the beginning, which results in missing the goal of the methodology. Therefore, in a first iteration, a model is made in which an overview is provided from the input streams, the main conversion parameters and the output products and waste streams. The process itself is more or less treated as a black box in which a certain conversion takes place.

The technical part is directly integrated with the economic part in which scale advantages are taken into account when calculating NPV, IRR and DPBP. The NPV gives an indication of the profitability of the biomass ECP using equation [1], where T is the life span of the investment, CF_n the difference between revenues and costs in year n, I_0 the initial investment in year 0, and i the discount rate. A biomass ECP is considered interesting when the NPV is positive (Fiala, Pellizzi, & Riva, 1997; Levy & Sarnat, 1994). When one has to choose between more than one biomass ECP concept (*i.e.* alternatives), the NPV ranking is mostly preferred over the IRR ranking (Lorie & Savage, 1955).

$$NPV = \sum_{n=1}^{T} \frac{CF_n}{(1+i)^n} - I_0 \qquad [1]$$

The model allows the user to alter the different input parameters and visualize the impact on both the mass and energy balance and financial viability of each concept. Finally, a summary sheet is included to allow the user to easily check the impact on the economic feasibility of an ECP concept and compare different concepts, without consulting all the underlying details. Figure 14 gives a visual representation of the model's structure. Although the structure is developed specifically for biomass ECP concepts, it can easily be adapted for other concepts as well.

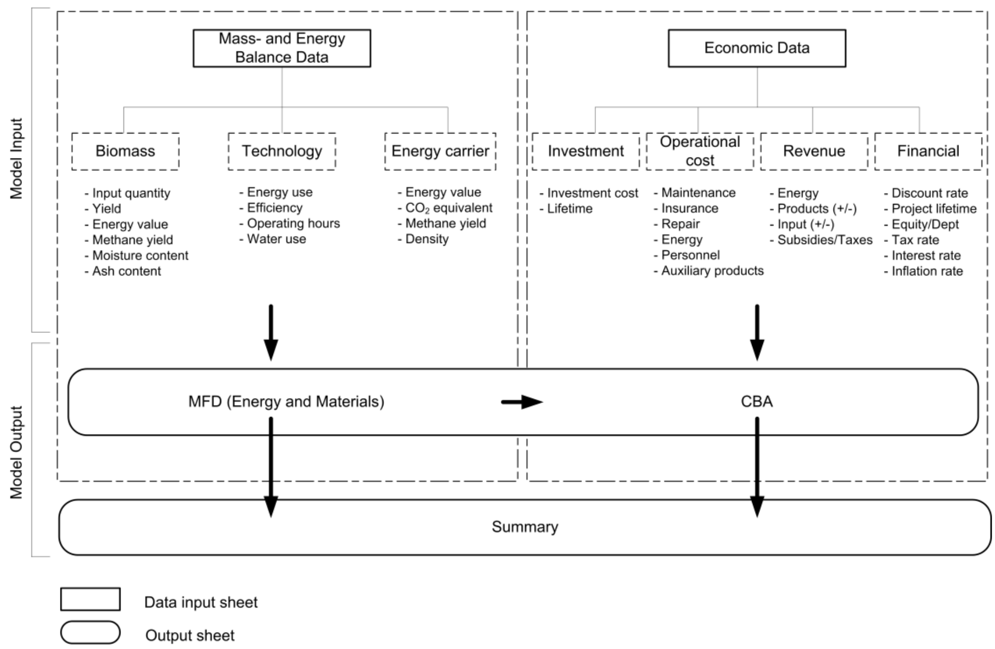


Figure 14. Schematic summary of the techno-economic evaluation method

The values which are used for the calculations within the model are deterministic rather than stochastic. Therefore, a Monte Carlo simulation (50,000 trials) is performed for each model. In a Monte Carlo approach uncertainty is characterized by assigning a probability distribution to input parameters and to simulate the output distribution by repeated random sampling. The analysis can be performed in five steps: (1) identification of key uncertain model input variables, (2) statistical description of risk for these key inputs by assignment of a probability distribution, (3) identification and statistical description of any relationship among the key inputs, (4) multiple iterations where sets of input assumptions are drawn from each specified variable's probability distribution, and (5) description of key model outputs by probability distribution (Spinney & Watkins, 1996). In our model the variables (technical as well as economic) are randomly varied following a triangular distribution with a positive and negative change of maximum 10%. The goal of this kind of quick scan is to determine the parameters that have the highest impact on the total uncertainty of the NPV. The analysis searches for the parameters that should be investigated into more detail. Moreover, when only literature data or expert judgments and no large datasets or historical data are available, only the lowest value, the highest value and the most likely value of the input variables can be assessed with large certainty, whereas the distribution is unknown. The triangular distribution is an adequate solution when literature is insufficient for deriving probabilities (Haimes, 2004). It is also the most commonly used distribution for modeling expert opinion (Vose, 2000). For this reason, the chosen distribution and ranges can be justified. Based on the results, more analyses have to follow on those parameters with the highest impact by varying them over realistic ranges. Results of these analyses provide some insight into the risk potential investors take. Based on the results of this first iteration, a decision can be made concerning the potential of this technology. In case the results are promising, a second iteration can follow with more detailed information on the critical success factors that were identified in the sensitivity analysis. However, when the results do not show the expected outcomes, it can either be decided to stop with the research or the results can help to refocus the research on the most critical parameters that have the highest influence on the economic feasibility.

Finally, it is clear that different phases within a TEA require multidisciplinary teams to execute the different phases of the analysis. However, too often the performers of the TEA are the technological developers of the technology, who carry out the assessment without the help of economists. Only rarely one of the authors can be explicitly identified as a fellow worker of an economic department of a university, a research institution or a government agency. This might be a disadvantage and raises questions concerning the accuracy of the analysis. It is advisable to carry out the evaluation with a multidisciplinary team, which provides more insight since different members of the team will ask different questions, have divergent interests and as such help to attain a broad picture of the innovation process.

In the next paragraphs the techno-economic evaluation method will be applied on two biomass ECP case studies.

3.3. Case study 1 – Breda

3.3.1. Introduction

It is chosen to perform a case study in the region of Breda, which is situated in the south-west of the Netherlands. This choice is motivated by the large available amount of biomass, the presence of high quality industries such as the agro, food, and chemistry industry, the supporting governmental attitude and the good accessibility via motor and waterways. This case study can be framed within the ECP-project (Interreg IVa) in which in total five different cases were analyzed. Every case started from a different phase within the development process. For the case study in Limburg no location was yet specified implying that the macro screening was developed in order to facilitate this process (see Chapter 2). However, in Breda the location was already specified, as a consequence, the macro screening was not applied on this case study.

First, an inventory of the available biomass waste streams in the local area (radius ca. 30 km) was made. Manure (pigs, cattle and poultry), residues from agro- and food-industry, organic municipal solid waste (OMSW), and residue wood appear to be the most available input streams. The characteristics of the different biomass types are listed in Table 8.

Table 8. Characteristics biomass input

	Wood	**Organic municipal solid waste**	**Manure**	**Residues agro- and food industry**
Quantity (ton/year)	1,419	64,000	16,000	8,000
Dry matter (%)	70	37.5	6	40
LHV (GJ/ton)	13	3	6	13
Biogas yield (Nm^3/ton)	NA	28	20.4	120

LHV = Lower Heating Value
GJ = Gigajoule

Based on the inventory, a biomass ECP concept (Figure 15) is developed. The integrated concept consists of two mono-dimensional models for which it will be proven that synergies exist due to scale advantages and a more optimal energy usage. All data is obtained from suppliers of the different processing technologies and literature. Three different models are evaluated:

- OMSW digestion (mono-dimensional): Organic municipal solid waste is digested in an Upflow Anaerobic Sludge Bed (UASB) reactor. The digestate is further composted and the biogas is sent to a Combined Heat and Power (CHP) engine.
- Co-digestion (mono-dimensional): Manure and co-substrates (residues from agro- and food-industry) are co-digested in a dry digester. The digestate is separated using three different steps and dried. The biogas is sent to a CHP engine. The expected heat shortage is remedied using a wood boiler on residue wood.
- Multidimensional model (*i.e.* ECP): Both processes are integrated using the residue heat from the OMSW digestion to solve the heat shortage of co-digestion. Consequently less wood is needed. Furthermore a single, bigger CHP engine can be used to convert the biogas, resulting in scale advantages.

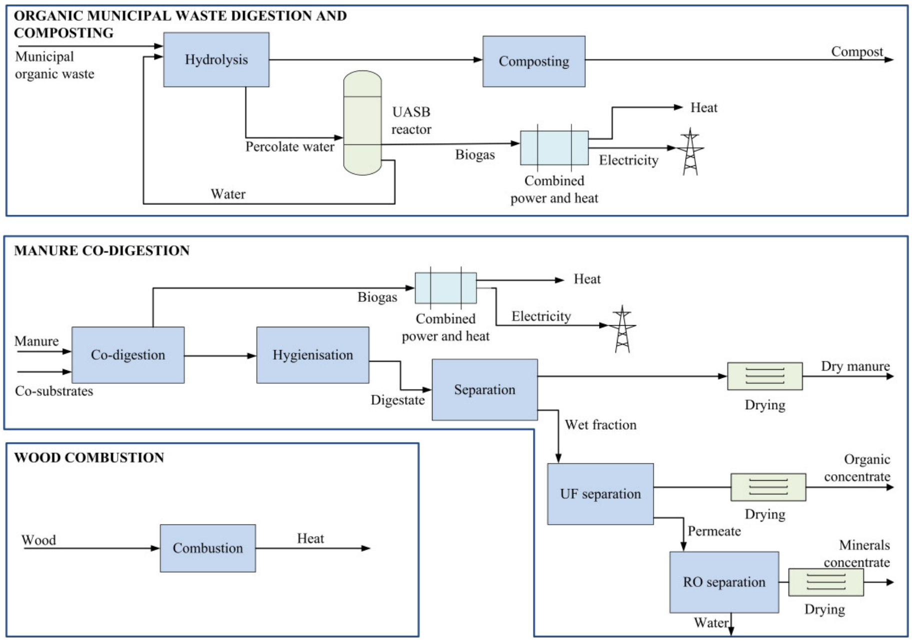


Figure 15. Schematic representation models

In the Netherlands different initiatives exist to promote the use of green energy. Of interest for the case study are the 'SDE+' subsidies and 'biotickets'. SDE+ works with a call system, which is opened in five different phases per year, with smaller subsidies in the first phases. As such, projects requiring less subsidies are given priority. Moreover, only a limited amount of money is available every year and if this amount is fully used in the first phase, the call is closed for the remainder of that year (S. Lensink, Wassenaar, Mozaffarian, Luxembourg, & Faasen, 2011; Staatsblad van het Koninkrijk der Nederlanden, 2007). Biotickets are provided to producers of biofuels. Distributors of gasoline and diesel are obliged to put a minimum percentage of biofuels on the market, in relation to their total volume of transport fuel sold on the Dutch market. Biofuels can be marketed either in pure form or mixed with fossil fuels. If a party has more biofuels than legally obliged, it can sell biotickets to other parties not fulfilling the minimum requirements. The price of a bioticket is determined by the market and should in theory cover the surplus cost of the necessary biofuels in order to bring an extra m^3 of fuel on the market. In 2011 the average price of a bioticket was 8 euro. At that time distributors were obliged to provide at least 4.25% biofuels to the market, implicating that one bioticket represents 1.5 GJ. In case the biofuel is produced from biomass waste or residue sources, or from lignocelluloses (*i.e.* second generation biofuels), this volume can be double counted, meaning that two tickets can be received from the same biofuel volume (groengasnl, 2012; Staatsblad, 2011). Note that biotickets are no direct subsidy but depend on market outcomes. The costs will be transferred to fuel prices, so they will be covered by transport fuel consumers. SDE+ subsidies cannot be cumulated with biotickets for the same installation.

3.3.2. Results

OMSW digestion (mono-dimensional)

The organic fraction of municipal solid waste can be composted, resulting in an added value material for soils (Barral, Paradelo, Moldes, Domínguez, & Díaz-Fierros, 2009; López, Soliva, Martínez-Farré, Fernández, & Huerta-Pujol, 2010; Odlare et al., 2011; Roe, Stoffella, & Graetz, 1997; Warman, Rodd, & Hicklenton, 2009). However, it is more interesting to first digest the OMSW to generate energy and afterwards compost the digestate to achieve enhanced waste processing (Hilkiah Igoni, Ayotamuno, Eze, Ogaji, & Probert, 2008; R. P. Singh, Tyagi, Allen, Ibrahim, & Kothari, 2011; Walker, Charles, & Cord-Ruwisch, 2009). The amount of compost that results is almost equal to solely composting and extra value is created from the energy production. In our model using an UASB reactor *ca.* 97%[1] of OMSW mass input can be composted. The remaining 3% of the input is transformed into biogas.

The input of the OMSW digester (UASB reactor) consists of 64,000 ton per year. From this a total of 1,792,000 m³ biogas is produced. The biogas has a methane yield of 55%. It is converted using a gas engine into 15,836 GJ of heat per year and 3,557 MWh of electricity. The overall efficiency of the gas engine is equal to 85% (Stroobandt, 2007). The digestate (97% of OMSW input) is composted to

[1] Ratio input to composting (%) = Input (1 ton/year) – (biogas production (28 Nm³/ton) * density biogas (0.0012 ton/Nm³))

form 23,183 ton of compost per year. In the process 33% of the produced heat is used. The produced electricity is not sufficient and the shortage in electricity has to be bought. In the model it is assumed that 50% of the remaining heat (*i.e.* total produced heat – internally used heat) can be sold to an external party at a distance of 1 km. The material flow diagram is represented in Figure 16.

Based on the material flows the economic feasibility can be evaluated. To this end, the investment cost, operational costs and revenues are determined. The lifetime of the project is assumed to be 15 years. The tax rate is, according to Dutch law, 20% for the first 200,000 euro and 25% for the remaining part (Belastingdienst, 2012). Furthermore, it is assumed that 50% is externally financed at an interest rate of 5% (Lantz, 2012). The inflation rate is set at 2%. Based on the above information, the weighted average cost of capital is calculated and amounts to 7% (Kalt & Kranzl, 2011; Voets, Kuppens, Cornelissen, & Thewys, 2011). The parameters and formulas used for the three different models to calculate the economic investment criteria are presented in Table 9. In the model it is assumed that the OMSW is processed by an intercommunal waste processing company. This is an entity that processes the waste of all inhabitants from a number of communities. Each community delegates one responsible to sit on the board of directors. A forfait per inhabitant can be taken into account. The forfait is a fixed amount paid per inhabitant of the participating communities to the waste processing company and is independent of the total amount of waste that is handled. In the model a total of 850.000 inhabitants (*i.e.* 75 kg/inhabitant/year) is taken into account (CBS, 2012). The OMSW is transported over a larger distance of ca. 45 km, instead of the assumed 30 km. However, the collection of OMSW is a service provided to communities which is independent of the type of processing afterwards. Since the digestion of OMSW with composting has a positive influence on the environment in comparison to incineration, this is worth considering (De Meester et al., 2012).

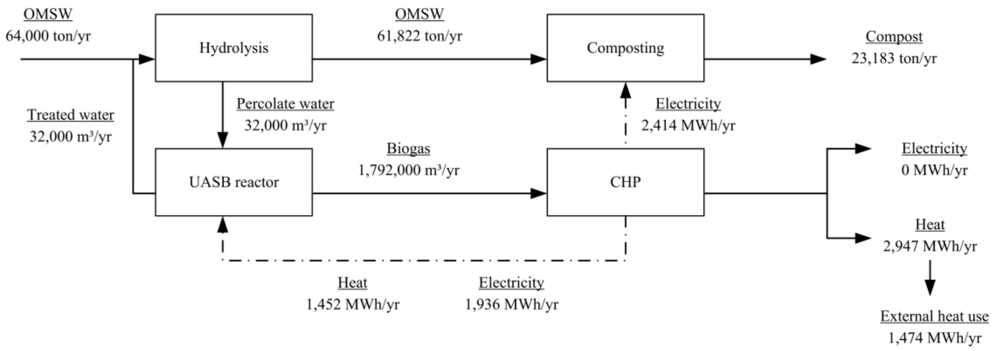


Figure 16. Material flow diagram for OMSW digestion

Table 9. Economic parameters

	Unit	Formula/Value
Investment costs		
UASB reactor [1,2]	M€	(1.7171 capacity (1,000 ton per year)$^{0.5581}$) 0.74
Lifetime UASB reactor [1]	yr	15
Gas cleaning [3]	€	If capacity (kWe) < 1,500 = $\frac{200,000}{1,500}$ capacity (kWe)) 1.1 Else = $\frac{200,000}{1,500}$ capacity (kWe)
Lifetime gas cleaning [4]	yr	10
CHP [3]	€	If the capacity (kWe) > 900 = (-386.1 LN(900) + 3,170.5) 1.2 Else = (-386.1 LN(capacity (kWe)) + 3,170.5) 1.2
Lifetime CHP [3]	yr	10
Composting [4,5]	€/ton	2,205,589 Input (ton)$^{-0.820}$
Lifetime composting [5]		15
Air treatment [4]	€	471,000
Lifetime air treatment [4]	yr	10
Heat network [6]	€/m	1,000
Lifetime heat network [6]	yr	15
Connection cost [6]	€/connection	30,000
Dry digester [7]	€/ton	748,770 input (ton/yr)$^{-0.804}$
Lifetime dry digester [7]	yr	15
Hygienisation [8]	€	$\frac{37,121 + 803\ (input\ (\frac{ton}{yr}))}{operating\ hours * density\ input\ (\frac{ton}{Nm^3})}\ 1.15$
Lifetime hygienisation [8]	yr	10
Separator [9]	€/m³/hr	15,661 input (m³/h)$^{-0.38}$
Lifetime separator [9]	yr	10

UFRO separator [8]	€	51,913 ((25,824 (liquid fraction (ton/yr))+15.61 (liquid fraction (ton/yr)-retentate (ton/yr))) 1.2 (1,000/(operating hours*seconds per hour))$^{0.6298}$
Lifetime UFRO separator [9]	yr	10
Dryer [10]	€/ton	15
Lifetime dryer [9]	yr	10
Wood boiler [11]	€/kW	1,322.1 capacity (kW)$^{-0.239}$
Lifetime wood boiler [11]	yr	10
Site preparation [12]	%I_0	10
Operational costs		
Repair	%I_0	2
Insurance [12]	%I_0	1
Maintenance UASB	%I_0	3
Analysis cost digester [7]	€/ton	1.67
Personnel digester [7]	#	1
Hourly wage rate [19,5,13]	€/hr	30
Maintenance CHP [3]	€/MWh	65.347 (capacity (kWe))$^{-0.1544}$ 0.9
Maintenance gas cleaning [3]	€/MWh	26,209 (capacity (kWe))$^{-0.1112}$
Maintenance composting [5]	€/ton	10
Operational composting [5]	€/ton	9
Red diesel [14]	€/l	0.941
Personnel composting [5]	#	input (ton per year)$^{0.8}$ 0.00094
Maintenance heat network [6]	%I_0	3
Maintenance dry digester [7]	%I_0	1.6
Maintenance separator	%I_0	3
Personnel separator [8]	hr/day	2
Maintenance UFRO	%I_0	3
Personnel UFRO [8]	hr/day	5
Maintenance dryer [8]	€/ton water evaporated	2.5
Personnel dryer [8]	hr/day	0.000875 thick fraction (ton/yr)
Maintenance wood boiler [15,16]	%I_0	3
Purchase cost wood [17]	€/ton	45
Ash disposal cost [12]	€/ton	110
Revenues		
Avoided cost electricity [18]	€/MWh	139.4
Sale green electricity [19]	€/MWh	50
Sale green heat [19]	€/MWh	20
Gate fee OMSW [5,20,21]	€/ton	60
Forfait OMSW [5]	€/inhabitant	5.4
Compost [5]	€/ton	4.96
Gate fee manure [10,18]	€/ton	25

Gate fee co-substrates [18]	€/ton	-5
Dry manure [22,23]	€/ton	-20
Dry retentate UF [22,23]	€/ton	-20
Dry retentate RO [22,23]	€/ton	3
SDE digester (CHP) basic [24,25]	€/GJ	19.444
SDE digester (CHP) correction[24,25]	€/GJ	11
SDE digester (CHP) lifetime [24,25]	yr	12
SDE digester (CHP) operating hours [24,25]	hr	5,739
SDE co-digester (CHP) basic [24,25]	€/GJ	19.444
SDE co-digester (CHP) correction [24,25]	€/GJ	11
SDE co-digester (CHP) lifetime [24,25]	yr	12
SDE co-digester (CHP) operating hours [24,25]	hr	5,739
SDE thermal conversion basic [24,25]	€/GJ	10.90
SDE thermal conversion correction [24,25]	€/GJ	9.10
SDE thermal conversion lifetime [24,25]	yr	12
SDE thermal conversion operating hours [24,25]	hr	7,000

UASB = Upflow anaerobic sludge bed
CHP = Combined heat and power
UFRO = Ultrafiltration and reversed osmosis
OMSW = Organic municipal solid waste
Sources:
1. Rapport, Zhang, Jenkins, and Williams (2008)
2. Helble and Möbius (2008)
3. Personal communication Stroobandt (2007)
4. Rijckeboer (2002)
5. Personal communication intercommunal waste processors
6. Hoogsteen, Braber, and Smit (2003)
7. Offers from three large manufacturers of dry digesters (2012)
8. Werf (2011)
9. VCM (2004)
10. Vandeweyer et al. (2008)
11. Moorkens and Briffaerts (2009)
12. Caputo, Palumbo, Pelagagge, and Scacchia (2005)
13. Belgian Federal Government (Brussels) (2008)
14. Esso ("Red diesel price," 2012)
15. Delivand, Barz, Gheewala, and Sajjakulnukit (2011)
16. Chau et al. (2009)
17. S. Lensink et al. (2011)

18. van Tilburg et al. (2008)
19. Voets et al. (2011)
20. Riet (2011)
21. Wille (2009)
22. Gebrezgabher et al. (2010)
23. Hoop, Daatselaar, Doornewaard, and Tomson (2011)
24. Ministerie economische zaken (2012)
25. AgentschapNL (2012)

Based on the CBA it can be concluded that the investment is economically feasible. The NPV amounts to roughly 11 million euro and the investment can be regenerated after 8 years.

Co-digestion (mono-dimensional)

Animal manure represents a constant pollution risk due to the emissions of greenhouse gases and leaching of nutrients and organic matter to the environment if not properly managed (Holm-Nielsen, Al Seadi, & Oleskowicz-Popiel, 2009). Legislation exists on European (Commission, 1991) as well as national level (Milieu, 1986; Rijksoverheid, 2012) to minimize this risk. Farmers are obliged to process their excess manure. Anaerobic digestion is one of the most efficient biological methods to reduce emissions. At the same time it recovers energy and produces a product that can be of added value in agriculture when further refined, being fertilizers, fiber products and clean water (Bustamante et al., 2012). In the model the digestate from the co-digestion is further separated and dried to produce the above mentioned products. Since these products cannot be used on agricultural soils in the Netherlands itself, due to overproduction of manure, these are transported cross border as added value products. In the Netherlands application standards for minerals are defined in legislation to protect the environment. It states that only part of the produced animal manure can be used on the field. The amount of animal manure that can be used, is formulated in the nitrate directive. On top of animal manure, fertilizer can be used to fill the remaining part of the standard per mineral. Although digestate, which is generated from animal manure using an industrial process, falls within the definition of fertilizer, it also fits the definition of animal manure in the nitrate directive. Therefore, these products have to meet the application standards of animal manure and thus cannot be used on the field (Commission, 1991).

Manure (16,000 ton per year) and co-substrates (8,000 ton per year) are co-digested. From the co-digestion 1,286,400 m³ of biogas results. This biogas has a methane yield of 57%. The resulting gas is converted further, using a CHP engine, into heat (11,785 GJ per year) and electricity (2,647 MWh per year). The digestate is separated using first a screw press and afterwards ultrafiltration (UF) and reversed osmoses (RO) resulting in 1,900 ton dry manure, 2,345 ton dry UF retentate and 820 ton dry RO retentate. The dried digestate is transported abroad where it is used as soil improver. The produced heat is not sufficient for the model, therefore, a wood boiler (1,419 ton per year) is used to provide sufficient heat for drying the digestate (Chau et al., 2009). The conversion process uses only 61% of the produced electricity, the remaining part is sold and put on the grid. All material flows are shown in Figure 17.

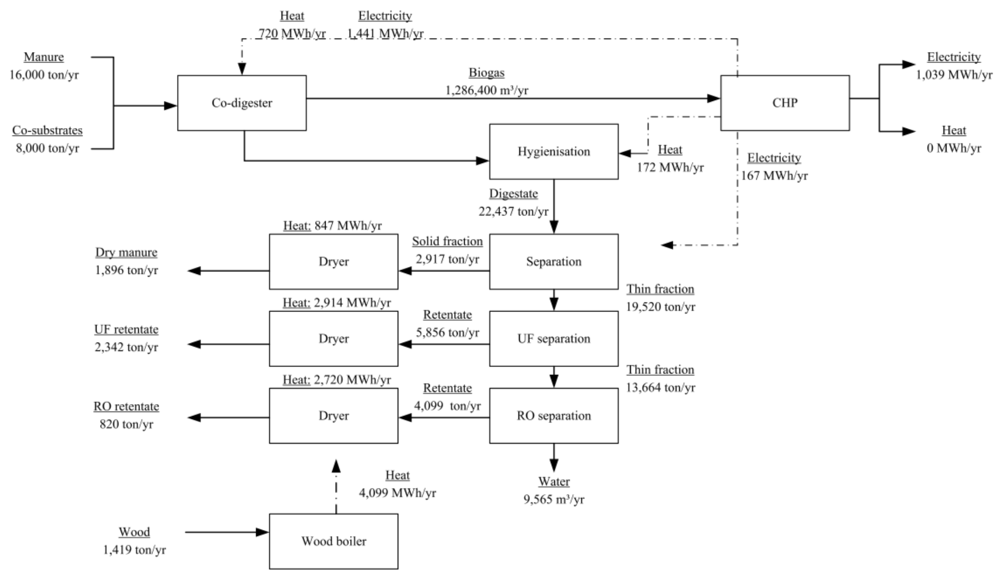


Figure 17. Material flow diagram for co-digestion

Using the economic parameters from Table 9 it can be concluded that the investment is economically infeasible. The NPV amounts to roughly minus 13.5 million euro and the investment cannot be regenerated in 15 years. This loss can be interpreted as the cost that should be paid for the right to produce livestock and granivores. As mentioned in the beginning of this paragraph, there is an overproduction of manure in the Netherlands, implying high processing costs in order to reduce environmental risk. This topic will be discussed further upon in section 3.3.3.

Energy Conversion Park (multidimensional)

In the energy conversion park model the previous two models are integrated to maximize energy efficiency. As mentioned before the first model has a heat residue and the second model requires a wood boiler to provide sufficient heat. Furthermore in both models biogas is converted using a gas engine and by combining both biogas streams into one CHP, scale advantages can be reached.

In the ECP model the same amount of inputs are converted into biogas resulting in 3,078,400 m^3 biogas per year. In contrast to the previous models the biogas is now combined into one larger CHP engine resulting in 27,621 GJ per year of heat and 6,203 MWh per year of electricity. The heat that is generated is not sufficient to provide the heat demand of the conversion process, however, less wood is needed to fill the remaining heat shortage. The conversion process uses 96% of the generated electricity, the surplus electricity is sold and put on the grid. The amount of compost, dry manure, dry UF retentate and dry RO retentate are the same as in the two separate models. The material flow diagram of the energy conversion park is displayed in Figure 18.

For the economic evaluation all information can also be found in Table 9. The resulting NPV equals circa 4 million euro. The IRR amounts to 10% and the investment could be regenerated within 12 years. A summary of the different results is shown in Table 10. A detailed overview of the total investment costs, expenditures and revenues for the different cases, can be found in Appendix 2. It can be concluded that it is more interesting to invest in the multidimensional model than in both separate models. The sum of the NPV of the two separate models equals minus 2 million euro whereas the NPV of the integration equals 4 million euro as mentioned above. Since the resulting NPV is highly dependent on the used parameters, the most influencing parameters are determined using sensitivity and scenario analysis. The results are explained in the next paragraph.

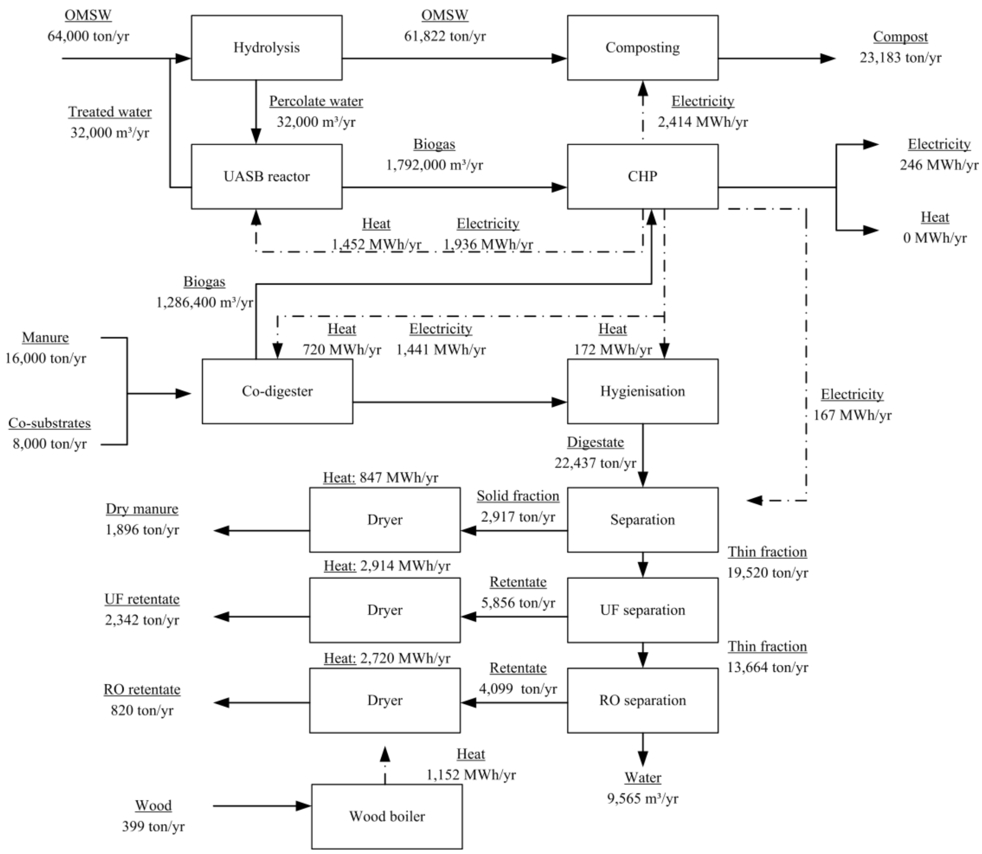


Figure 18. Material flow diagram for ECP

Table 10. NPV, IRR and (discounted) payback period

	OMSW digestion (1)	Co-digestion (2)	Sum OMSW digestion and co-digestion (1+2)	ECP (3)
NPV (€)	€ 11,378,112	€ -13,477,410	€ -2,099,298	€ 3,834,710
IRR (%)	16%	-		10%
PBP (year)	5.74	>15		7.55
DPBP (year)	7.47	>15		11.98

NPV = Net present value
IRR = Internal rate of return
PBP = payback period
DPBP = discounted payback period

Sensitivity and scenario analysis

For the calculation of the NPV the values shown in Table 9 are used. These values are deterministic rather than stochastic. Therefore, a Monte Carlo simulation (50,000 trials) is performed for each model, varying the variables following a triangular distribution with a positive and negative change of maximum 10%. The goal of this kind of quick scan is to determine the parameters that have the highest impact on the total uncertainty of the NPV. The analysis searches for the parameters that should be investigated into more detail. For this reason, the chosen distribution and ranges can be justified. Based on the results, more analyses have to follow on those parameters with the highest impact by varying them over realistic ranges. Table 11 summarizes the variables that contribute more than 6% to the total uncertainty in the NPV of the different models. It can be concluded that one of the main contributors to the total uncertainty in the NPV are the gate fees in each model. In the OMSW digester and the multidimensional or ECP model the forfait that is collected per inhabitant and the number of inhabitants have the highest influence. Their high influences on profitability can be explained by the certainty of having a fixed revenue that is independent of the amount of biomass processed. Other factors that have an influence on the total uncertainty in the NPV are the investment cost of the composting installation and digester. Furthermore, it appears that current policy support has little influence on the profitability of these two models. Conversely, in the co-digestion model the subsidy has an influence on the variation in the NPV, however, this influence is small in comparison to the influence of the investment cost of the digester and UFRO separator. Moreover, the same parameters have the highest influence on the sum of the NPV of both separate models as on the multidimensional model, even though the NPV of the multidimensional model is much higher. It can be concluded that integrating both models, does not necessitate a reorientation of the investor's focus points. An overview of the sensitivity of the NPV of the ECP case to the variations in the different parameters is provided in Figure 19. In the remainder of this section the parameters that have the highest impact on the total uncertainty in the NPV of the multidimensional model are further investigated.

Table 11. Relative contribution of the variables' range to the total uncertainty in NPV

Variable	Relative contribution to NPV total uncertainty (%)			
	OMSW digestion	Co-digestion	Sum OMSW digestion and co-digestion	ECP
Number of inhabitants (#)	+26.9		+25.7	+24.9
Forfait OMSW (€/inh)	+26.2		+26.3	+26.1
Gatefee OMSW (€/ton)	+19.1		+17.2	+17.8
Input OMSW (ton/year)	+9.1		+9.0	+10.4
Investment cost composting (€)	-7.0		-6.2	-6.2
Investment cost digester (€)	-6.2		-6.3	-6.4
Investment digester (€)		-40.4		
Investment UFRO separator (€)		-13.4		
Gate fee manure (€/ton)		+9.5		
SDE co-digester basic (€/GJ)		+7.5		

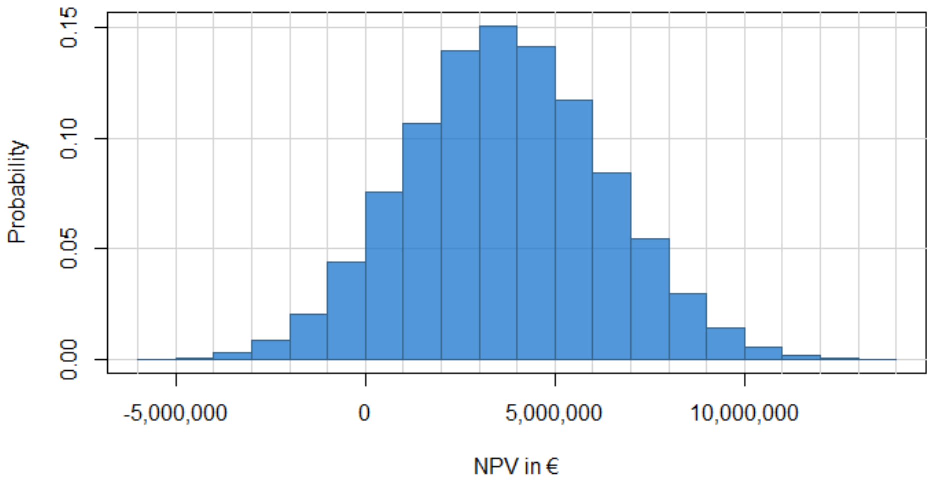


Figure 19. Probability distribution of NPV for ECP Breda

As already mentioned a forfait per inhabitant cannot be taken into account when the OMSW reactor is exploited by a private investor. Therefore, in a first scenario analysis the NPV is recalculated without taking into account the forfait per inhabitant. For the OMSW digester (see (1) in Table 10) the NPV declines from 11 million to minus 23 million euro and for the integrated model (see (3) in Table 10) from 3.8 million to approximately minus 32 million euro. From these results it can be concluded that private investors will be reluctant to invest in an OMSW digester. Therefore, in countries having an intercommunal waste processor, a biomass ECP that includes the processing of OMSW can only be exploited in collaboration with an intercommunal waste processor. Since private investors do not have a fixed revenue per inhabitant, they have to compensate this loss by asking gate fees that are not market conform. When in these countries the intercommunal waste processor is not involved in the biomass ECP, the organic fraction of MSW cannot be considered as a biomass residue stream. On top, another advantage of the forfait is the incentive it creates to bring OMSW to the installation and as such assure a constant input stream. This makes it even more difficult for private investors in countries with intercommunal waste processors to profit from a digester using OMSW.

In a second scenario analysis the impact of the gate fee on the NPV is further investigated. The demand for biomass is rising, going side by side with increased pressure on biomass prices. According to the sector, the gate fee of OMSW will certainly be lowered to 40 euro per ton. Figure 20 gives a graphical representation of the impact of the gate fee on NPV of the multidimensional model. The central line represents the NPV for different values of the forfait per inhabitant when the gate fee of OMSW amounts to 40 euro per ton. The upper and bottom line represent the boundaries between which the gate fee can vary. It can be concluded that the multidimensional model is economically feasible with a gate fee of 52 euro per ton other parameters *ceteris paribus*. When only investing in the OMSW digester the gate fee can decrease to approximately 35 euro per ton.

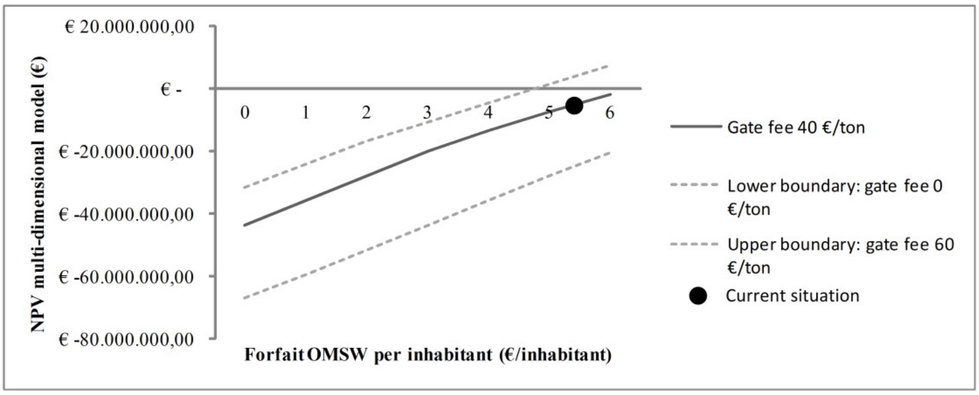


Figure 20. Impact gate fee OMSW on NPV ECP

In both the Netherlands and Belgium the majority of the composting installations, run by intercommunal waste processing companies, are already depreciated. This implies that only operational costs for the composting installation need to be paid and that the investment of approximately 16.5 million euro should not be taken into account. This assumption has a large impact on the gate fee of OMSW as illustrated in Figure 21. Under these assumptions it would be possible to lower the gate fee of OMSW to 40 euro and at the same time lower the forfait per inhabitant to 3,2 euro.

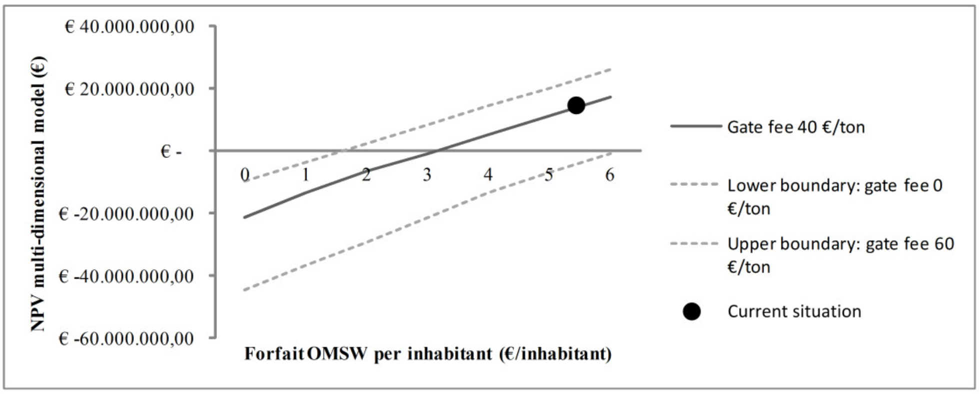


Figure 21. Impact gate fee OMSW on NPV ECP with depreciated composting installation

For the digestion of the OMSW an UASB digester was used. However, an alternative is to use a dry digester (Murphy & McKeogh, 2004). A dry digester has the advantage that the biogas yield is higher, *i.e.* 100 m³/ton in comparison to 28 m³/ton for UASB digestion. Furthermore, the investment cost is lower. The disadvantage of the dry digester is that the digestate cannot be composted directly. However, when the resulting digestate is mixed with garden waste it can be further composted and a costly water treatment plant is avoided. In total 35,000 ton of garden waste is mixed with 56,223 ton of digestate which result from the dry digestion of 64,000 ton OMSW. The conversion of biogas using the CHP engine results in 68,343 GJ of heat and 15,349 MWh of electricity. Within the model 81% of the produced electricity and 57% of the heat is used. The economic parameters can be found in Table 9. For the garden waste only a forfait per inhabitant of €0.98 is taken into account. The resulting NPV amount to *ca.* 18 million euro, implicating that the gate fee of OMSW can be lowered to 19 euro per ton. When no forfait per inhabitant is taken into account for OMSW, nor for garden waste, a negative NPV of minus 20.5 million results. However, if it is assumed that the composting installation is fully depreciated, the NPV of the integrated model with two dry digesters becomes marginally positive.

3.3.3. Discussion

From this analysis it is shown that by using an ECP it is possible to process different biomass streams in an economically feasible manner. However, from sensitivity analyses it is shown that chances are high of having a non-profitable installation. The simulation shows that gate fees, the number of inhabitants and forfaits are the main drivers for a profitable installation. Furthermore, the investment cost of the UASB digester and composting installation have a major impact on the variation in the NPV of the multidimensional model, therefore, the authors recommend on the one hand to use a dry digester and mix the digestate with garden waste to allow for the production of valuable compost and on the other hand to add the digester to an existing, depreciated composting installation.

From a socio-economic point of view the analysis shows that it is economically and energetically more interesting to invest in the multidimensional model than in two separate models. NPV of the multidimensional model is indeed higher than the sum of the NPVs of the separate models. However, from an investor's standpoint one should invest in the OMSW digester, given that this model results in the highest NPV. According to many authors (Al Seadi, 2004; Bustamante et al., 2012; Holm-Nielsen et al., 2009; Lantz, 2012) supporting programs, e.g. investment grant or feed-in-tariff, should be introduced to stimulate recycling of wet organic wastes. The stimulation of multidimensional models could be an answer to this call, since these models require far less support to convince private investors than the promotion of the mono-dimensional co-digester. By promoting integrated models environmental benefits such as the saving of fossil energy, greenhouse gas savings, decreased water use, reduction of transport distances, less pollution and traffic burden result. Examples of these environmental benefits, resulting from this case study, are: (1) in the mono-dimensional OMSW digestion model, electricity has to be bought, whereas in the multidimensional model sufficient electricity is generated, (2) when using a dry digester to convert OMSW in a multidimensional concept, no wood has to be used to provide the internal heat, (3) in the Netherlands it is obliged by law to process manure due to overproduction, however, the mono-dimensional co-digestion concept is not economically feasible, whereas the multidimensional model is.

On top of the economic and energetic benefits of the biomass ECP model, the digestate of the co-digestion of manure can be refined to products that are of added value in agriculture. For example, it can be used as a substitute for chemical fertilizers, which are nowadays not only imported from large distances but also produced using high amounts of fossil fuel (Ramírez & Worrell, 2006). The usage of digestate as a valuable product is also recognized by other authors. Bougnom, Niederkofler, Knapp, Stimpfl, and Insam (2012) concluded that the combination of anaerobic sludge and wood ash have both a positive effect on soil chemical parameters as well as on total forage yield. Also Abubaker, Risberg, and Pell (2012) call for attention of the residue quality in the future development of biogas energy. From the sensitivity analysis it can be concluded that investment costs to convert manure into these valuable products have the largest impact on the total uncertainty in the NPV. This cost has to be compensated by revenues that result from the high economic value of these materials. However, the digestate is considered as a waste product in the Netherlands, due to legislation, for which operators have to pay for. When legislation allows for applying the digestate on agricultural land as substitute for fertilizer, its value will increase. Furthermore, heat demand will lower drastically since the digestate does not have to be dried and transported cross border any more. This allows for an alternative usage of the biogas, since it no longer has to be used in a CHP to provide sufficient heat in the process. It can, for example, be upgraded to green gas or liquid biomethane (LBM), creating a high value product (Murphy, McKeogh, & Kiely, 2004).

3.4. Case study 2 – Moerdijk

Based on the conclusions of the first case study, focus will shift in the second case study to materials. Energy will be seen as a by-product following the cascading principle. This implies that the second case study is moving towards a concept that can be situated within the emerging bio-based economy.

3.4.1. Introduction

The bio-based economy deals with the transition from the production of materials, chemicals and energy based on fossil hydrocarbons, towards one that is based on renewable biological resources (Cherubini et al., 2009; Langeveld, Meeusen, & Sanders, 2010). Factors as climate change, rural development, dependence on politically unstable regions, and strong price fluctuations of fossil fuels are the driving forces for this transition (Ghatak, 2011; Yan & Lin, 2009). On a worldwide scale, research and development programs are being introduced to promote the efficient use of biomass (Carole, Pellegrino, & Paster, 2004; Communities, 2004; Villela Filho et al., 2011). Even though the core of the Dutch policy vision on the bio-based economy aims at efficient and intelligent use of biomass, most of the existing biofuels and bio-chemicals are currently produced in unidimensional production chains, relying on clean and valuable biomass sources (Asveld, Est, & Stemerding, 2010). The same applies to Europe (Cherubini, 2010; Márquez, Reumerman, Venselaar, Broeze, & Pelkmans, 2012). Such chains often do not use biomass to its full potential and they strongly rely on government support. Residual heat (or other energy flows) remains untapped and residues are not valorized, implying that these need to be transported for further processing. The concept of an ECP with focus on materials, rather than energy, can answer to these concerns. Therefore, it is chosen to perform a case study for Moerdijk (51° 39’ NB, 4° 32’ OL). Next to Limburg (see Chapter 2) and Breda (see section 3.3), Moerdijk is another case study within the ECP project (Interreg IVa).

Moerdijk is a municipality with important industry and harbor facilities, which is situated in the province of Noord-Brabant in the Netherlands. As a first step, an inventory is made of the available biomass residue sources (*i.e.* supply), existing biomass processing facilities, and demand of predominantly energy requirements of local companies in a radius of 30 km around Moerdijk. Since Moerdijk itself is rather small, this implies 29 different communities are taken into account. Depending on the specific biomass residue source it can be justified in some cases to deviate from the prescribed radius of 30 km (see *infra* section 3.4.2). From the inventory a list of companies involved with biomass was selected to which a questionnaire was sent. From 82 companies contacted, however, only 13 companies responded. Therefore, the most important companies from the list were identified and interviews were arranged with the companies that showed interest. The interested parties were gathered in a sounding board and were actively involved during the further development of the ECP concept. During the interviews it was possible to obtain a complete view of current activities, visions and regional needs. The close collaboration with the sounding board allowed the further integration of the ECP within the regional frame. Furthermore, the information collected during the interviews indicates that Moerdijk is an industrial environment with considerable bioenergy related activities and few residential/urban biomass. Additionally, Moerdijk has a good logistic connection (e.g. port), a supply of heat greater than the demand, and a gas grid which is already used to its full capacity. From this it is concluded that no heat should be provided by the ECP and no green gas can be injected into the grid.

Based on the inventory and interviews some ECP concepts were developed that matched the available biomass with the local demand and supply of energy (mainly heat). These concepts are the main working documents for the second step. In this step, the most important stakeholders are identified and gathered in a focus group to discuss, based on the results from step 1, which of the developed ECP concepts are most interesting for the region. Besides discussing which of the developed concepts will be most interesting, they also indicated which technology is undesirable. Also a discussion was held about other types of output that might be of more value for the region and whether certain biomass streams can be valorized more efficiently. Stakeholders consist of local governmental parties and companies that are involved or intending to invest in biomass and bioenergy developments in the region. The involvement of the main stakeholders early in the process increases chances of acceptance and realization of the concept (Voinov & Bousquet, 2010). In the third step, the techno-economic spreadsheet model was applied on the chosen ECP concept for Moerdijk.

3.4.2. Results

Using the regional biomass inventory, the main biomass input streams for the ECP case in Moerdijk are identified. Local owners of biomass were interviewed to determine the contractible amounts, specifications, and the conditions for further cooperation. The main available biomass input streams in the region of Moerdijk are provided in Table 12. Some streams are collected in large scale, and are therefore in theory available in large quantities. However, ongoing projects in the region for these biomass streams forced us to consider only part of them available for the ECP. Wood residues and waste fats have a high value, therefore, a larger area can be taken into account. However, a market already exists for these streams, so only a small part is taken into account in order not to disrupt this market. Nature grass and roadside cuttings do not have a high value, therefore, only the western part of Noord-Brabant is taken into account. Since roadside and ditch cuttings are not valorized yet, 100% is available for the ECP concept. Nature grass is already partly processed and thus only 50% is taken into account. Organic municipal waste is collected separately in the Netherlands and 100% can be available for the ECP concept. However, only the organic municipal waste of Moerdijk and the municipalities in the immediate vicinity are taken into account because transport costs are too high. Manure is widely available in the Netherlands. However, processing manure has a negative impact on the ECP concept due to its high moisture content and low energy value. Therefore, it is opted to only process a small fraction of the available manure in the region of Moerdijk. Despite the negative impact on the ECP concept, it is chosen to process a small fraction of manure as it is obligated to process excess manure in the Netherlands. Technical aspects of the biomass residue streams are provided in Table 13.

The ECP concept for Moerdijk was built around four “key” conversion technologies: (1) grass refinery, (2) anaerobic digestion and gas upgrading, (3) pyrolysis, and (4) biodiesel production through esterification. Energy and material resources are exchanged between the different technologies in order to use the biomass to its full potential. Using the techno-economic evaluation model the resulting material and energy flows are determined. The ECP concept and the associated material and energy flows are shown in Figure 22.

Table 12. Available biomass for the ECP in Moerdijk

Biomass	Theoretical potential [ton/year]	Area	Percentage available for ECP	Net available [ton/year]
Natural grass	108,186	West-Brabant	50%	54,093
Roadside and ditch cuttings	25,174	West-Brabant	100%	25,174
Wood residues	356,400	The Netherlands	14%	50,000
Organic municipal solid waste	15,799	Moerdijk region	100%	15,799
Cattle manure	524,023	Moerdijk region	5%	26,201
Pig manure	182,464	Moerdijk region	5%	9,123
Waste fats	1,215,000	The Netherlands	5%	60,750

Moerdijk region = Moerdijk, Steenbergen, Halderberge, Etten-Leur, Breda, and Drimmelen

Table 13. Technical parameters of the biomass for the ECP in Moerdijk

Biomass	Moisture content [%]	Energy value [GJ/ton]	Biogas potential [Nm³/ton]	Methane yield [%]
Natural grass[1]	80	-	90	55
Roadside and ditch cuttings[2]	60	-	85	57
Wood residues[3]	15	16	-	-
Organic municipal solid waste[2]	52	-	100	55
Cattle manure[a; 2,4]	88	-	54.3	55
Pig manure[a; 2,4]	88	-	62.1	60

[a] after separation in thin and thick fractions

Sources:

1. Nizami and Murphy (2010)
2. Offers from three large manufacturers of dry digesters (2012).
3. Saidur, Abdelaziz, Demirbas, Hossain, and Mekhilef (2011)
4. Delzeit and Kellner (2013)

In the grass refining technique the harvested grass is pressed to obtain two main products, *i.e.* the press juice (rich in proteins) and fiber rich residues. The proteins can be recovered by heating the press juice until the protein gets a fixed shape. The proteins first coagulate or flocculate and can then be separated (van den Pol-Dasselaar, Durksz, Klop, & Gosselink, 2012). According to literature, more than 70% of the initial proteins can be recuperated using grass refinery (Kuyper, Linnemans, & Hesselink, 2011). Since nature grass contains 177 g/kg dry matter (DM) of proteins for an input of 54,093 ton this results in 1,340 ton of proteins that can be used as animal feed (O'Keeffe, Schulte, Sanders, & Struik, 2011). The juice residue fraction is mixed with the fiber residues. The mixture with a moisture content of 80% is dried to 60% moisture content and in a next step anaerobically co-digested with other biomass streams.

Production of biodiesel from oils and fats can be done via esterification. Biodiesel is produced through a chemical reaction between oils/fats and methanol. Glycerol, the secondary product, can be used as input stream in the anaerobic digester. Second generation biodiesel is produced from residues, such as waste fat in this case study, so there is no competition with food applications.

The thick fraction of manure, grass juice residue, glycerol, OMSW and roadside and ditch cuttings are processed using the dry anaerobic digestion technology. The manure separation step itself is not part of the ECP. Separation of manure in thick and thin fractions occurs at the farm level. The retention time in the anaerobic digester is approximately 25 days under thermophilic conditions. In order to process the input streams (approximately 75,000 ton), two digesters of 3,586 m^3 are necessary. Note that the optimal size of the digester is 3,950 m^3 (Personal communication with manufacturer of digesting installation in Belgium, December 18 2012). This implies that scale advantages are optimally used. The biogas produced is upgraded to natural gas quality and further liquefied to obtain bio-LNG (*i.e.* liquid biomethane). The other two options of biogas valorization (*i.e.* production of heat/electricity or injection of green gas in the natural gas grid) are less attractive for Moerdijk. Remind that the current supply of heat is greater than demand in the Moerdijk industrial area, and that the injection possibilities of green gas into the natural gas grid are already used to their full capacity. The biogas produced (6.2 million Nm^3) contains around 52% of methane (CH_4), with significant amounts of CO_2 (around 40%). In comparison with natural gas, biogas additionally contains various contaminants, such as hydrogen sulfide (H_2S) and ammonia (NH_3). Hydrogen (H_2), nitrogen (N_2), hydrocarbons, and oxygen (O_2) are sometimes present in smaller quantities. Furthermore biogas is saturated with water, and sometimes contains solid particles. In order to process the biogas further, it is necessary to remove these contaminants to a greater or lesser extent. The essential and the most costly step is the removal of the CO_2. For this, there are several proven techniques available, in the case study the absorption with water (pressurized water wash) is selected. Production of bio-LNG can be seen as the next step in the biogas upgrading. The gas, rich in biomethane (around 97%), is cooled to below 112.15 K, at this temperature the gas is liquefied.

The residual stream from the digester, the digestate, accounts to 67,000 ton. Because manure is part of the digester input stream, the digestate cannot, due to legislation, be spread on the land (Commission, 1991). The digestate is dried to a moisture content of 5% (reduction of *ca.* 60% in moisture content) and sent to a pyrolysis installation. Also Delzeit and Kellner (2013) argue that in regions where only a small amount of agricultural land is available to spread digestate, processing digestate increases profitability of biogas production. The dried digestate is co-pyrolysed with dried wood residues. In this context pyrolysis is also used as a separation technology between the organic matter and the ashes (rich in minerals). In the case study fast pyrolysis is used in order to maximize the production of pyrolysis oil (*i.e.* 54 m%). The pyrolysis oil contains approximately 50% of the energy input. The biochar (*i.e.* 16 m%) and pyrolysis gas (*i.e.* 30 m%) are used to provide internal energy in the pyrolysis reactor, as well as to the other processes (Rogers & Brammer, 2012).

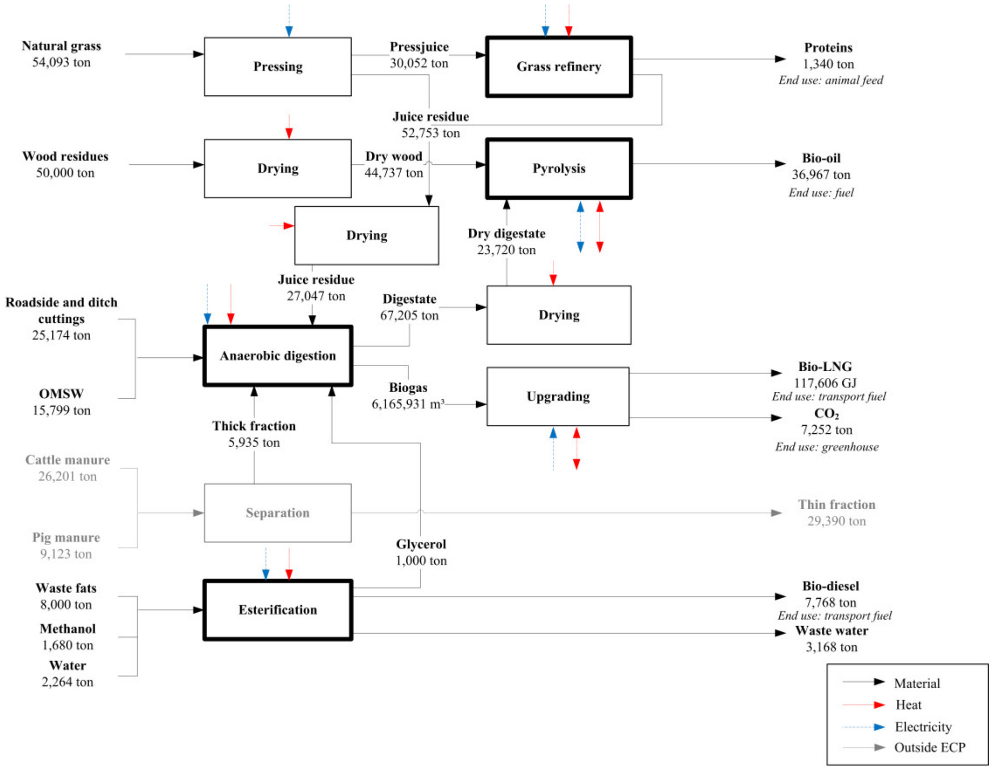


Figure 22. ECP concept Moerdijk

According to the calculations, electricity can be provided internally. The remainder of the electricity is sold to the grid. The amount of heat that can be provided internally is insufficient. Therefore, heat is bought from an external heat source. Since the supply of heat in the region of Moerdijk is greater than the demand, this is not a problem. An overview of the energy calculations, consumption and production of the different processes is provided in Table 14. These amounts can be linked to the red and blue arrows in Figure 22.

Table 14. The energy consumption and production in the ECP of Moerdijk

Conversion process	Source		Value/Formula
Pyrolysis[1,2]	Heat consumption	MWh	36,130
		Formula	2 GJ/ton
	Electricity consumption	MWh	2601
		Formula	40 kWh/dry ton
	Heat production	MWh	73,072
	Electricity production	MWh	15,658
Anaerobic digester[3]	Heat consumption	MWh	3271
		Formula	10% of biogas energy
	Electricity consumption	MWh	3926
		Formula	12% of biogas energy
Dryer digestate	Heat consumption	MWh	44,796
Grass refinery[4]	Heat consumption	MWh	811.4
		Formula	270 MJ/dry ton
	Electricity consumption	MWh	246
		Formula	22.7 kWh/dry ton
Dryer residue juices	Heat consumption	MWh	26,384
Biodiesel production[5]	Heat consumption	MWh	8545
		Formula	1.1 GJ/ton biodiesel
	Electricity consumption	MWh	466
		Formula	60 kWh/ton biodiesel
Pressing installation	Electricity consumption	MWh	1451
		Formula	3 kWh/ton
Dryer wood	Heat consumption	MWh	5422
Upgrading installation[6,7]	Heat consumption	MWh	3700 (recovery 3330)
		Formula	0.6 kWh/m³ (90% recovery)
	Electricity consumption	MWh	493
		Formula	0.08 kWh/m³ biogas
External source	Heat production	MWh	52,658
	Electricity consumption	MWh	6475

Sources:

1. Rogers and Brammer (2012)
2. Bridgwater, Toft, and Brammer (2002)
3. Offers from three large manufacturers of dry digesters (2012)
4. O'Keeffe et al. (2011)
5. Zhang, Dubé, McLean, and Kates (2003)
6. Dumont (2009)
7. Offer from manufacturer upgrading installation (2013)

To assess the feasibility of the ECP concept, an economic appraisal is required. The ECP concept was evaluated using the spreadsheet model, taking into account an economic lifetime of 10 year and a weighted average cost of capital (WACC) of 7%. A short depreciation period of 10 year is chosen to indicate the feasibility of an ECP concept for potential private investors. Longer evaluation periods of 15 to 20 year are only feasible for public investors. Furthermore, the discount rate provides a return requirement and reflects the risk the company attributes to the investment. For investments with a medium risk factor, a discount rate of 10% is often chosen. When assuming that 50% will be externally financed at an interest rate of 5%, this results in a WACC of around 7%. The different economic parameters that were taken into account are provided in Table 15.

Table 15. Economic parameters for the ECP in Moerdijk

	Unit	Value/Formula
Investment		
Shredder[1]	€	$\left(\frac{\text{input in ton}}{44{,}737\text{ ton}}\right)^{0.6} 193{,}489$
Digester[2]	€/m³	1,369,105/(reactor volume)$^{0.81}$
Pyrolysis[3]	€	3,486,567 (input in ton dm/h)$^{0.6914}$
Grass refinery[4,5]	€	$\left(\frac{\text{input press in ton}}{123{,}889\text{ ton}}\right)^{0.6} 51{,}136 + \left(\frac{\text{input refinery in ton}}{41{,}758\text{ ton}}\right)^{0.6} 655{,}232$
Esterification[6-9]	€	$(63.45\frac{€}{Mg} * biodiesel\ in\ ton) + 3{,}938{,}879$
Upgrading[10,11]	€/Nm³ biogas/h	200,510 (input in Nm³/h[1])$^{-0.686}$
Bio-LNG production[10]	€/Nm³ biogas	0.1
Dryer	€/ton	35
Site preparation	%	10%
Operational costs		
Purchase water[12]	€/m³	0.65
Disposal water	€/m³	30
Repair	%I_0	2

Insurance[13]	$\%I_0$	1
Purchase price electricity[14]	€/MWh	100
Purchase price natural gas[15]	€/GJ	7.24
Purchase price heat[16]	€/MWh	20
Personnel[17]	€/h	30
Maintenance shredder	$\%I_0$ shredder	3%
Analysis cost digester[2]	€/ton input	1.67
Personnel digester[2]	# FTE	3
Maintenance digester[2]	$\%I_0$ digester	1.6
Maintenance pyrolysis[3]	$\%I_0$ pyrolysis	5
Personnel pyrolysis[18]	# FTE	8
Maintenance grass refinery[5]	$\%I_0$ grass refinery	10
Personnel grass refinery[5]	# FTE	1
Maintenance esterification[9]	$\%I_0$ esterification	10
Personnel esterification[7,9]	# FTE	8
Disposal ash[19]	€/ton	122
Maintenance Upgrading[10]	€/Nm³ biogas/h	200
Compression gas[10]	€/Nm³ biogas/h	$42.043*(\Delta p\ bar)^{0.5894}$
Quality control[10]	$\%I_0$ upgrading	1
Maintenance bio-LNG	€/Nm³ methane	0.03
Maintenance dryer[20]	€/ton water damped	2.5
Residue fats	€/ton	600
Methanol[21]	€/ton	340
H_2SO_4	€/ton	164
Purchase price wood[14]	€/ton	55
Revenues		
Selling price electricity[16]	€/MWh	50
Selling price heat[16]	€/MWh	20
Gate fee OMSW[22]	€/ton	40
CO_2[23]	€/ton	30
Bio-LNG[24]	€/ton	550
Pyrolysis-oil[25]	€/GJ	12
Bio-diesel[24]	€/ton	690
Gate fee manure[a; 14]	€/ton	15
Proteins[4]	€/ton	500
Bioticket[b; 26,27]	€/GJ	5.35

Inputs are expressed as yearly input amounts, unless otherwise indicated.

FTE = Full Time Equivalent

dm = Dry Matter

[a] Gate fee = disposal cost

[b] In the analysis we have chosen for the use of biotickets instead of the SDE+ subsidy, since biotickets can be double counted.

Sources:

1. Ulrich (1984)
2. Offers from three large manufacturers of dry digesters (2012)
3. T. Kuppens (2012)
4. Kuyper et al. (2011)
5. O'Keeffe, Schulte, Sanders, and Struik (2012)
6. Zhang et al. (2003)
7. Vlysidis, Binns, Webb, and Theodoropoulos (2011)
8. Marchetti, Miguel, and Errazu (2008)
9. Apostolakou, Kookos, Marazioti, and Angelopoulos (2009)
10. Vandeweyer et al. (2008)
11. Offer from manufacturer upgrading installation (2013)
12. DACE (2011)
13. Ng and Sadhukhan (2011)
14. Lensink (2012)
15. CREG (2011)
16. Voets et al. (2011)
17. FPS Economy (2004)
18. Thewys and Kuppens (2008)
19. M. Kuppens et al. (2011)
20. van der Werf (2011)
21. Methanex (2012)
22. Personal communication intercommunal waste processors, Belgium (2012)
23. EEX (2013)
24. BPF (2013)
25. Christis (2012)
26. groengasnl (2012)
27. Staatsblad (2011)

The resulting NPV of the ECP concept amounts to 6 million euro, the IRR is 11% and the DPBP is less than 8 year. By combining the different unidimensional models, economic synergies are revealed. The sum of the NPVs of the separate unidimensional models (*i.e.* grass refinery, anaerobic digestion and gas upgrading, pyrolysis, and esterification) amounts to -10 million euro. By combining the different processes energy and material streams can be interchanged. From Table 16 it can be concluded that, besides the ECP concept, only the unidimensional processes of esterification and pyrolysis are economically interesting under the assumptions made. Interesting is that by combining proven technologies with technologies that are in a demonstration phase, the range of technologies that can be implemented in an economically feasible way is broadened. An overview of the total investment costs, expenditures and revenues is provided in Appendix 3.

Table 16. NPV, IRR and discounted payback period

	Digestion (1)	Grass refinery (2)	Esterification (3)	Pyrolysis (4)	ECP (5)
NPV [€]	-16,930,250	-7,461,313	5,661,331	3,987,710	5,619,466
IRR [%]	-	-	45	14	11
DPBP [year]	>10	>10	2.47	6.81	7.77

NPV = Net present value; IRR = Internal rate of return; DPBP = Discounted payback period

Since many parameters are uncertain, a Monte Carlo simulation (50,000 trials) is performed for the ECP concept, varying the variables following a triangular distribution with a positive and negative change of maximum 10%. The sensitivity analysis is first performed by varying all parameters (*i.e.* technical and economic), including investment costs. In this analysis the investment cost of the digester is the most important parameter and explains almost 50% of the variation in the NPV. The energy value of residue wood and the amount of biodiesel produced explain respectively 12.6% and 7% of the variation. The bio-oil yield, price of bio-oil and investment cost of the pyrolysis installation each explain another 4.4% of the variation in the NPV. An overview of the relative contribution of the variables' range to the total uncertainty in the NPV is provided in Table 17.

Table 17. Relative contribution of the variables' range to the total uncertainty in NPV

Variable	Relative contribution to NPV total uncertainty (%)
	ECP
Investment cost digester (€)	-42.6
Energy value residue wood (GJ/ton)	+12.6
Biodiesel production (%)	+7.0
Bio-oil yield (%)	+4.4
Price bio-oil (€/GJ)	+4.4
Investment cost pyrolysis installation (€)	-4.4

In a second analysis, the investment costs are not taken into account. By varying the different other parameters over their range, the NPV can vary between -17 and 24 million euro (see Figure 23). This range of 41 million euro confirms the importance of the sensitivity analysis. Gaining sufficient insight is essential in understanding risk. From this second analysis it seems that (1) the energy value of the waste wood, (2) the amount of biodiesel, (3) the price of pyrolysis oil, (4) the amount of pyrolysis oil, and (5) the price of biodiesel have the highest influence on the total uncertainty in the NPV. Combined they explain 64% of the variation in the NPV. It can be concluded that esterification and pyrolysis are the most important processes for the economic feasibility of the ECP concept. These technologies also produce high value products which provide the largest part of the revenues (*i.e.* together more than 50%). Prices of pyrolysis oil, biodiesel and biotickets have the highest influence. The price of bio-LNG and proteins has a minor impact on the economic feasibility. If the system of biotickets would not be available, the NPV of the ECP concept would lower drastically. Additionally, biodiesel production itself would be economically infeasible. Furthermore, when receiving only a single bioticket, biodiesel production would still be uninteresting.

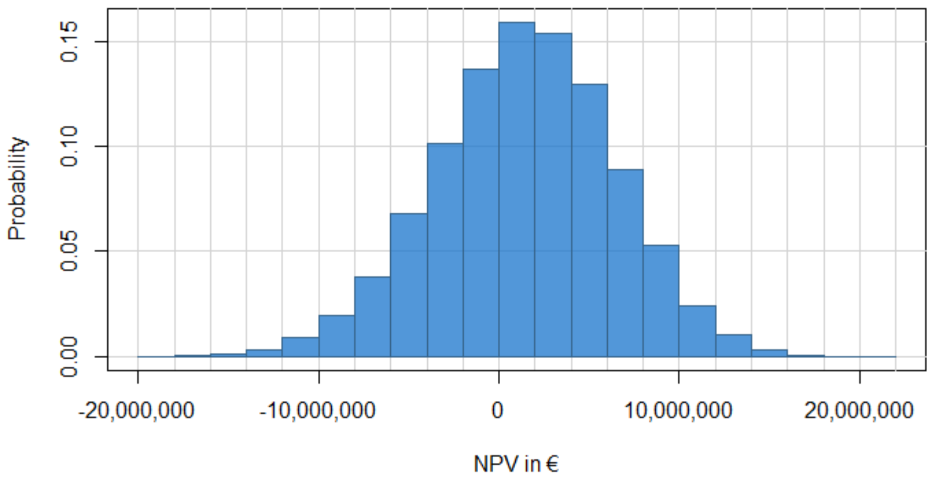


Figure 23. Probability function NPV for ECP Moerdijk

3.4.3. Discussion

From the sensitivity analysis it can be concluded that certain price parameters can heavily influence the total picture, so the interest of private investors in an ECP concept will depend on their expectation of future market trends. If they expect prices of different products to increase in the future, resulting in a sufficiently high IRR, they may be inclined to take the risk. Menrad, Klein, and Kurka (2009) conclude from their cross-European survey that the industrial attitude towards biorefineries is positive. However, efficient production of a portfolio of biobased products has not yet been implemented. Although criticism exists concerning biofuels, experts consider current biofuel production as one of the frontrunners for the further development of biorefinery concepts. Note that second generation biofuels is even more relying on integrated processes to reach sufficient efficiency (Caspeta, Buijs, & Nielsen, 2013). Based on the results of the case study, this can also be confirmed. On top, a step-by-step integration is more likely in practice. Companies will, based on our case study, first invest in a pyrolysis or biodiesel installation and later on add other technologies to it. The specific conditions and prices under which these kinds of decisions, *i.e.* investments under uncertainty, which are sometimes irreversible and/or can be delayed, will be taken, can be analyzed using the theory of real options which is based on dynamic programming (Dixit & Pindyck, 1994).

As the goal of this research is to indicate the feasibility of a biorefinery concept which can be implemented on a short term, focus is on proven technologies and technologies that are already in a demonstration phase. For example, in the study it is opted to take a more conventional type of grass refinery into account, however, ongoing studies take a look at the opportunities of grass refinery to produce high value products such as lactic acid (O'Keeffe et al., 2011). Also, in the case study focus is not on nutrient recovery, while, recent studies indicate the potential of nutrient recuperation. For example, Vaneeckhaute, Meers, Michels, Buysse, and Tack (2013) studied the ecological and economic benefits of the substitution of conventional fertilizers by digestate derivatives. Azuara, Kersten, and Kootstra (2013) studied the potential of phosphorus recovery from char after fast pyrolysis. Furthermore, the biochar can still be used for the energy provision of the pyrolysis reactor, as in the developed ECP concept. Yoder, Galinato, Granatstein, and Garcia-Pérez (2011) provide an economic tradeoff model between biochar and bio-oil production, depending on the pyrolysis temperature and prices of both products. These kinds of models can be used to further optimize economic feasibility of an ECP concept depending on the local situation. Biochar can, besides soil amendment, after activation also be used as filter medium, e.g. as carbon dioxide adsorbent in flue gas, or as dye removal in waste water industry, resulting in different economic values (Rebitanim, Wan Ab Karim Ghani, Rebitanim, & Amran Mohd Salleh, 2013). Focus on biochar or bio-oil production will, therefore, depend on the chosen end-use. However, even more interesting is to optimize both biochar and pyrolysis oil production (Brown, Wright, & Brown, 2011). As indicated in this study, the production of high value materials can significantly improve the economic feasibility of biorefineries. Therefore, further research should indicate the economic impact of these promising innovative activities.

3.5. Discussion and conclusion

To attain the 20-20-20 targets of renewable energy, biomass waste streams are an interesting source for energy production. In the region of Breda/Moerdijk the main potential biomass waste streams available for the production of renewable energy are manure, OMSW, roadside cuttings, residues of the agro- and food-industry and residue wood. These are converted into energy and materials using a biomass ECP, which is proven to have advantages in comparison to the separate conversion of the different biomass waste streams. When focusing on waste streams, it can be concluded that it is necessary to add a digester or other technology to the biomass ECP that allows for the processing of wet streams. Holm-Nielsen et al. (2009) argue that 25% of all bioenergy production can come from these wet organic streams in the future.

From this analysis it is shown that by using an ECP it is possible to process different biomass streams in an economically feasible manner. However, from sensitivity analyses it is shown that chances are high of having a non-profitable installation. Therefore, policy is of major importance in the future development of biomass ECP (Peck, Bennett, Bissett-Amess, Lenhart, & Mozaffarian, 2009). In our models the electricity and heat, which are produced by the process and are used internally, are valued as an avoided cost seeing that otherwise electricity would have had to be bought from the grid. From the analysis, it can be concluded that the impact of the avoided cost on the NPV is large. Therefore, a decision of the government not to allow taking an avoided cost into account would drastically lower the economic feasibility. However, only if the avoided costs are the consequence of usage of a public utility, the government is able to have an impact on avoided costs. This could have been the case for photovoltaic solar panels (PV panels). PV panels insert their produce on the electricity grid when it is not consumed in-house. Since the usage and production of electricity in case of solar panels is not synchronized, the grid is used bi-directional. Hence, the owners of solar panels could have been forced to pay a compensation for this bi-directional use of the grid, causing their avoided cost of electricity to decrease. However, in case of an ECP the production and usage of electricity is at the same time and the grid is only used in case of a shortage or excess of electricity production. The government might put restrictions on the amount of electricity that can be put on the grid, but taking into account that this amount is very small (*i.e.* the electricity produced is mainly used internally), the economic impact of such a decision will be very small. Furthermore, if no support is provided by the government, it is unlikely that investors will start new biobased concepts. Governmental support can be provided either by financial support (e.g. investment grant or operational support) or obligations (e.g. quota). However, most important is the guarantee of a stable investment climate in which support is not changed regularly resulting in increased risks for investors. As can be seen from practice only biodiesel and digester installations are implemented on an industrial scale in The Netherlands. This might be explained by the fact that government obliges companies to provide a minimum amount of green transport fuels, provides subsidies or obliges to process excess manure. Alternatively, it might be the case that investment costs for e.g. digesters are lower if the investor can partly build the installation himself. This way a positive impact on the economic feasibility results. Still, from the number of digesters that fail in practice, it can be concluded that the economic feasibility is uncertain and can vary from year to year depending on market conditions. It can, therefore, be concluded that further research has to clarify what the exact reasons are for the early investments in biodiesel and digester installations. In order to attain the goal of processing biomass residue and waste streams, governments should promote biorefineries, *i.e.* highly efficient and integrated processing of biomass. Hence, the processing of waste streams such as OMSW, verge cuttings and manure is very important considering their negative impact on the environment when badly managed. As shown in the case study using a combination of conventional and more innovative processes, a concept can be developed in which there is much lower need for government support. Note that still some support mechanisms, such as quotas, are essential in order to attain a positive NPV for the combination. Either way, due to economic synergies, governments have to provide less subsidies in order to attain their goal when they promote biorefineries in comparison to the separate technologies. In addition, it is indicated that revenues are provided by high value products and not by electricity and heat. Therefore, biomass projects should focus more on these high value products, whereas electricity and heat should only be byproducts. Government should therefore extend their current support mechanisms towards these higher value products. However, by doing so, it should be kept in mind that fulfilling the European targets for renewable energy is still an important driver for governments. Therefore, in the next chapter the sustainability assessment, used to determine whether the energy products can be taken into account for the European targets, is evaluated.

Chapter 4.

Environmental Assessment*

* *Parts of this section have been published in:*
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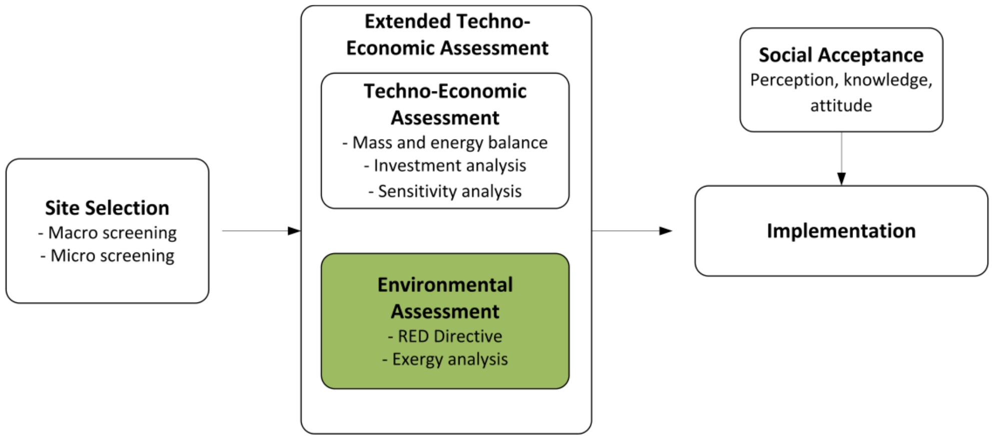
Apart from the techno-economic evaluation, provided in the previous chapter, also a sustainability calculation has to be incorporated. By incorporating the environmental analysis one can speak of an extended TEA. This allows answering the question whether a biorefinery is also desired from the viewpoint of the society. Only when the products produced within the biorefinery are sustainable, it is interesting for the society. It is even more interesting if the products can be taken into account for attaining the 20-20-20 targets of the Renewable Energy Directive 2009/28/EC (*i.e.* RED). Note that the 20-20-20 targets are binding and that the European Commission may proceed with sanctions when European member states do not succeed in attaining the targets. Therefore, it will be checked whether the products produced in a case study which is very comparable to the case of Moerdijk (*i.e.* case 2 in Chapter 3) can be taken into account for the targets and at the same time make an evaluation of the calculation guidelines as prescribed in the RED and compare them with calculations based on exergy.



4.1. Introduction

There is an increasing demand for biological materials for the production of energy and fuels. A public concern to preserve the sustainability of these developments is reflected in the rapid evolution of sustainability guidelines and rules set out by governments and international institutions. The sustainability of products is a complex issue that depends on numerous factors (Clancy, Fröling, & Svanström, 2013) and, therefore, these rules are very diverse. There is growing consensus on the importance of measuring the Greenhouse Gas (GHG) impact in most guidelines, but other aspects such as land use change, food security, social impacts or sustainable water use, remain hard to integrate in all official sustainability measurements (Scarlat & Dallemand, 2011). Related policies supporting renewable energy and fuel production need important design improvements. General practical pathways of sustainable fuel production can be set out, for instance the use of biological waste streams or the growth of perennial plants on degraded farmland. But the current policies require significant improvements before these can nudge bioenergy production pathways towards these solutions (Tilman et al., 2009).

In itself, assessing the sustainability of a biofuel production pathway is a challenging task. There are several explanations for the contradictory results regarding the sustainability of biofuels. For example, the variations in the GHG performance of biofuels are often due to differences in local conditions and the design of the specific production system, different calculation methods and system boundaries (Börjesson & Tufvesson, 2011). Many methodologies are an application of Life Cycle Assessment (LCA), as it aims to consider the impacts during the whole life cycle of biofuels. However, several problems of bioenergy LCA studies related to the use of input data, functional units, allocation methods, reference systems and other assumptions have been identified (Cherubini & Strømman, 2011).

This empirical difficulty is only increased with innovative bioenergy technologies. Straightforward production pathways consist of one or two cultivated streams of biomass that are transformed to one type of energy carrier. Sustainability assessments of these single pathway technologies are clear-cut in terms of attribution, allocation and categorisation of streams. In contrast to single pathways, innovative bioenergy pathways are often combined to create economic synergies and environmental benefits. This gives rise to elaborate and flexible biomass supply chains (Gold & Seuring, 2011). Innovative transformation processes of biomass can produce simultaneously materials and energy flows. New combustion projects not only focus on clean sawdust or wood particles, but also polluted streams (Nzihou & Stanmore, 2013). Fermentation projects combine various flows of biomass, such as roadside clippings (Pick, Dieterich, & Heintschel, 2012), organic municipal waste and agricultural by-products (Weiland, Verstraete, & Van Haandel, 2009). These projects produce energy flows such as heat, and electricity, but also other products, such as fertilizers, liquefied biogas, purified CO_2 or animal fodder (Van Dael, Van Passel, et al., 2013). Novel processes continue this development to the production of renewable hydrogen (Urbaniec, Friedl, Huisingh, & Claassen, 2010). Also microalgae are gradually fit in new production chains (Holma et al., 2013). Higher degrees of complexity are achieved by biorefineries (Bozell, 2008). Based on the principles of green chemistry (Manley, Anastas, & Cue Jr, 2008), these concepts are integrated plants creating a vast range from renewable energy carriers to high value chemical products in a sustainable set-up (Warner, Cannon, & Dye, 2004). This higher degree of integration can lead to more environmental benefits (Demirbas, 2009), but also to more exigent sustainability assessments.

Due to these trends, sustainability assessment methods face difficulties to assess such complex processes holistically (Maes & Van Passel, 2014). Translating this sustainability assessment in binding legal regulations is even more challenging, and requires coherence with other legal instruments and international agreements. The European Union (EU) has historically been proactive in the creation of official sustainability rules for renewable energy, biobased fuels and gases. Despite other contradicting EU initiatives, the sustainability rules and regulations drafted by EU policies remain important predecessors for other likeminded initiatives anywhere in the world (Afionis & Stringer, 2012). Within the legislative body of the EU, the European Renewable Energy Directive 2009/28/EC (RED) forms an important part of the entire European energy policy, and a crucial part in any future structure of international biofuel trade (Kaditi, 2009). The RED (EC, 2009), and the related COM/2010/11 (EC, 2010b) provide guidelines for calculating GHG impact in order to guarantee the sustainable use of renewable sources. These sustainability guidelines are essentially based on CO_2 equivalent emissions over the entire life cycle of the biomass project. The calculations are complemented with controls for sustainable land use and respect for social rights. Research projects already addressed several important advantages and limitations of the RED sustainability guidelines. There are for instance difficulties to correctly account for indirect land use change and local variability (Van Stappen, Brose, & Schenkel, 2011). Soimakallio and Koponen (2011) also discuss related topics, such as trade-offs, timing and allocation problems. Tufvesson et al. (2013) conclude that the current calculation method has a limited systems perspective since the actual utilization of some residues is not included in the calculations. Also the core, the GHG accounting, is being discussed. When comparing three different GHG accounting methods, diverging results for partial life cycle assessments are found (Whittaker, McManus, & Hammond, 2011). Even more precisely, Hennecke *et al.* (2013) compare two calculation tools that are both based on the RED guidelines, and still show diverging results.

Given the importance of the RED-guidelines, this paper adds to this strand of research by looking at the effects of legal uncertainty in the analysis of complicated production processes with multiple bioenergy pathways. Such complex pathways result in the co-production of different resources. Much depends on the classification of the resource streams as material or waste for which the RED guidelines follow other legal texts. A concise review of the legal state-of-art concerning this waste regulation shows that the choice whether a resource is waste remains often debatable. Furthermore, where multiple outputs are generated, the RED provides an allocation rule. But the allocation rule departs on particular instances from standard biophysical allocation procedures. These aspects have a large impact on the results of the sustainability assessment. In order to investigate the effect of the RED focus on single pathways directed towards fuels and energy, we apply the RED guidelines to an advanced Energy Conversion Park (ECP) in the Netherlands (Van Dael, Márquez, et al., 2013). The ECP is a complex multiple pathway structure, producing fuels, energy and materials. The sustainability analysis is performed according to the RED guidelines using the Bioenergy Sustainability Assessment Tool (B-SAT) and compared to those of a Cumulative Exergy Extraction from the Natural

Environment (CEENE) analysis (J. Dewulf et al., 2007). The results are compared particularly in relation to the horizon of the analysis over the biomass pathway, and the effect of different allocation rules for output valuation.

The chapter is structured as follows. Section 4.2 provides the principal details of the RED guidelines that are shaped by the single pathway approach and provides more details about the legal framework concerning waste. Section 4.3 describes the four potential legal scenarios as a result. It also elaborates the two sustainability assessment methodologies that will be used to analyse the four scenarios. Section 4.4 presents the general set-up of the ECP and the sustainability assessment results. Section 4.5 discusses and concludes.

4.2. Consequences of multi-pathways for the RED guidelines

The easiest case of renewable energy production is composed of one single process, utilising a group of inputs and producing one single renewable energy stream as output. Divergence from this single pathway case can happen on multiple occasions in the production chain, and causes uncertainty to apply the RED guidelines. (1) The process itself can produce multiple energy streams and materials as outputs. The emission burden of the process will have to be allocated among the different outputs, and this requires an allocation rule. (2) Earlier in the production chain, inputs can be the result of other industrial activities. Inputs only carry an emission burden covering their entire preceding production chain if they are valuable. Waste materials from industrial activities do not carry this burden. The decision whether an input is a waste material or not, has therefore a strong effect on the result of the sustainability analysis. (3) The energy production process can be split into multiple interconnected processes. The sustainability can be either analysed for every single process separately, or this division can be disregarded and the entire site can be analysed as a black box with multiple outputs. This principal decision has again strong effects on the results.

This section focuses on the principles related to occasions (1) and (2). The RED guidelines provide an allocation rule for co-products. The differences with other related allocation rules will be discussed. The principal decision whether a material is waste or not, is subjected to the evolution and interpretation of the related laws and regulations. The third point and its effect will be analysed in sections 4.3 and 4.4.

4.2.1. Choices in the allocation rule

In multi-output processes, the emissions are distributed by allocation. Allocation in a life cycle perspective is a debated issue because of the various solutions for allocation and the ensuing impact of these solutions on the final results (Ekvall & Finnveden, 2001). The existence of recycling loops within a life cycle chain makes the results particularly sensitive to allocation decisions (Vogtländer, Brezet, & Hendriks, 2001). For the analysis of processes where co-products are inevitable, the RED provides an allocation rule according to the energy content of the co-product (EC, 2010b). This rule has been criticized as not every co-product is destined to be used as an energy carrier, so the allocation rule according to energy content is not always appropriate (Soimakallio & Koponen, 2011).

There is ambiguity in the principles of the RED to transfer emission burdens over the production chain. The general framework of the RED guidelines reflects biophysical standard rules for Greenhouse Gas accounting. These rules are on a few instances altered by principle decisions, and finally, the sustainability practitioner can determine several assumptions. This unusual mixture of objective rules and principle decisions shows the compromise that is embedded in the RED guidelines. The allocation rule in the RED-guidelines presents distinct differences with other allocation rules based on biophysical measures, and these differences hint at the existence of principal choices rather than at objective sustainability criteria.

The RED allocation rule is based on the Lower Heating Value (LHV) of the fuels. The energy content of a fuel can be described in terms of higher heating value (HHV) as well as in lower heating value (LHV). The difference between the two definitions is small for solid fuels, large for liquids and very large for gaseous energy carriers. LHV does not account for the latent heat in water vapour formed at the combustion of fuels. This latent heat cannot easily be recovered for all types of fuel use. But the use of LHV is much more common in the energy production sector. So the choice to base allocation on LHV is a step bringing the rule closer to the practical calculation procedures of the energy sector. However, this step comes at the cost of smaller precision and a disproportionate advantage for gaseous and liquid biofuels over solid biofuels. Additionally, many wet material flows cannot be evaluated in LHV, so this principal choice limits the future extensions of the guidelines to deal with material flows.

For heat flows, only the qualitative energy part can be accounted for. The transformation between the entire energy quantity and the qualitative part is calculated using the Carnot efficiency, as integrated in the RED allocation rule. However, the Carnot efficiency drops significantly for low-temperature heat flows. The RED guidelines account for any low-temperature heat flow as if it would have a fixed minimal temperature of 150°C. This is very high in practice and rarely encountered in small scale bioenergy projects. Therefore, the rule can be seen as a principal choice to give a disproportionate advantage to bioenergy projects managing to valorise low-temperature heat.

4.2.2. Legal state-of-the-art on the definition of waste materials

According to the RED principles (EC, 2009), waste used as an input does not carry an emission burden and the waste generated during production does not reduce the carbon burden of the material produced. When waste is generated during the process, the related emissions are attributed solely to the material produced. The decision is thus reduced to the question whether a particular input or output is waste or not. The RED guidelines do not provide criteria for this principal decision. Therefore, an important question for this research is when biomass is waste or not, and, if it is waste, when it ceases to be waste. Actually, this question is the subject of debate for many years now. In fact, the European waste policy is one of the oldest topics within European environmental policy and it started in the mid-70s with the first Waste Framework Directive of 15 July 1975 (EEC, 1975). This directive was codified in the Directive 2006/12/EC (EC, 2006). Since 12 December 2010 the current basic legislation with regard to waste is the Waste Framework Directive of 19 November 2008 (EC, 2008). This directive repealed and replaced the directive of 2006.

Throughout the past decades, the most important question related to the Waste Framework Directive has always been whether the directive applies to certain goods or substances, or in other words how 'waste' is defined. According to article 3.1 of the Waste Framework Directive (EC, 2008) 'waste' means "A*ny substance or object which the holder discards or intends or is required to discard.*". The European Court of Justice has consistently interpreted this definition in a broad way. However, a too broad interpretation imposes unnecessary costs on the businesses concerned, and can reduce the attractiveness of materials that would otherwise be returned into the economy. On the other hand, an excessively narrow interpretation could lead to environmental damage, and undermine Union waste law and common standards for waste in the EU (EC, 2007). The first evidence to determine whether a material is waste or not, is whether the manufacturer deliberately chose to produce the material in question. If the manufacturer could have produced the primary product without producing the material concerned but chose to do so, then this is evidence that the material concerned is not a production residue. Other evidence that the production of the material concerned was a technical choice could include a modification of the production process in order to give the material concerned specific technical characteristics. Even where a material is considered to be a production residue, it is not necessarily a waste. The characteristics of the material in terms of its readiness for further use in the economy can mean that it should not be considered to be a waste. The Waste Framework Directive sets out a four part test that a substance or object must meet in order to be considered as a by-product and not as waste: (a) further use of the substance or object is certain; (b) the substance or object can be used directly without any further processing other than normal industrial practice; (c) the substance or object is produced as an integral part of a production process; and (d) further use is lawful, *i.e.* the substance or object fulfils all relevant product, environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts.

The Waste Framework Directive also contains a procedure for defining end-of-waste (EoW) criteria, which are criteria that a given waste stream has to fulfil in order to cease to be waste (EC, 2008). Waste streams that are candidates for this procedure must have undergone a recovery operation, and comply with a set of specific criteria. These criteria are to be developed in accordance with the following conditions: (a) the substance or object is commonly used for specific purposes; (b) a market or demand exists for such a substance or object; (c) the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and (d) the use of the substance or object will not lead to overall adverse environmental or human health impacts. The European Commission is now working on preparing proposals for end-of-waste criteria for specific waste streams. One of the aimed waste streams is biodegradable waste. In the Communication from the Commission on future steps in biowaste management in the European Union (EC, 2010a), the European Commission states that compost and digestate from biowaste are under-used materials. Furthermore, it is mentioned that the end-of waste procedure under the Waste Framework Directive could be the most efficient way of setting standards for compost and digestate that enable their free circulation on the internal market and to allow using them without further monitoring and control of the soils on which they are used. In July 2013, the Joint Research Centre's Institute for Prospective Technological Studies (JRC-IPTS) published a draft final report on end-of-waste criteria for biodegradable waste subjected to biological treatment (IPTS, 2013). The IPTS prepared this study with technical information to support the proposal for end-of-waste criteria for biodegradable waste subjected to biological treatment. Besides describing the criteria, the study includes all the background information necessary for ensuring conformity with the conditions of Article 6 of the Directive.

From the above discussion it can be concluded that in order to calculate the sustainability of end-products, the RED guidelines require an allocation rule, a decision framework to determine waste streams, and a principal decision to investigate all processes individually or to investigate the entire site as a black box. This still leaves room for interpretation and thus induces uncertainty for the results of the sustainability assessment. In this paper the influence of this uncertainty is analysed by means of different legal scenarios applied to the case study (see Table 19 and Table 20).

4.3. Methodology

In order to investigate the impact of the above mentioned requirements on the sustainability calculation, different scenarios are constructed. Within the dissertation the B-SAT-tool[1] is used, *i.e.* a specialised calculation tool to assess sustainability according to the RED guidelines. Not all scenarios can be assessed with B-SAT, and therefore a more generalised sustainability method, CEENE (J. Dewulf et al., 2007), is used.

The sustainability of all end-products of a multiple pathway production process has to be evaluated. This will be done with four different scenarios, based on two distinct decisions (see Table 18). The first decision concerns the determination of waste flows. Two scenarios regard some input streams, intermediate streams or output streams as waste. Two other scenarios regard those streams as material. The second decision concerns the level of detail of the analysis. Two scenarios look at one industrial process at a time, transfer emission burdens to the resulting outputs and continue to the next process of the site, until the final end-products are evaluated. Two other scenarios only look at the inputs and outputs of the entire site and keep the internal exchanges and workings hidden as if the site was a black box.

[1] B-SAT tool VITO: http://emis.vito.be/b-sat

Table 18. Overview of four scenarios investigated

		Labels legally uncertain streams as waste	
		Yes (Waste streams)	*No (Material streams)*
Looks at the combination of multiple processes as one black box	*Yes (BB : Black Box)*	BB-waste	BB-valuable
	No (IP : Individual Processes)	IP-waste	IP-valuable

B-SAT is a software tool developed at the Flemish Institute for Technology (VITO) in Belgium[1]. The tool is based on the calculation guidelines of the EU RED and the standard input data from the BioGrace tool[2]. B-SAT is targeted for all types of stakeholders involved in biomass projects enabling them to perform a rough sustainability analysis themselves. The sustainability framework of the B-SAT software offers the possibility to check compliance with the sustainability requirements in the EU RED (impact categories (i) and (ii)) and in addition, seeks to address all three dimensions (*i.e.* environmental, social and economic) of sustainability. The considered impact categories are the global warming potential (GWP), biodiversity and effect on high carbon stocks (above and below ground), the energy balance of the process, acidification and eutrophication potential, water and land use, and social impacts. The social impact is divided into two parts: (1) the risk of violation of human and property rights, and (2) the working conditions, including health and safety at work, fair wages, legal contracts and workers' rights.

The CEENE methodology follows the cumulative use of exergy during the life cycle of a product. Exergy or 'available energy' has been defined as "*The maximum amount of useful work that can be obtained from a system or resource when it is brought to equilibrium with the surroundings through reversible processes in which the system is allowed to interact only with the environment*." (Jo Dewulf et al., 2008). Compared to energy, the exergy concept is much more precisely defined, and applicable not only to energy flows but also

[2] EC recognized GHG calculation tool: http://www.biograce.net

to flows of matter. Different forms of energy cannot be counted together. Exergy eliminates these restrictions and provides a common basis for all energy forms: mechanical, chemical, electrical, thermal or potential. Moreover, the cumulative use of exergy building up during the life cycle allows including both direct energy use and 'grey energy' (*i.e.* energy being used for mineral resources, the manufacturing of intermediate products, or resources used up in the production). The CEENE extends the Cumulative Exergy Content (CEC), which accounts for all exergy streams including material inputs to the process, such as minerals or gases (Szargut, 2005; Szargut, Morris, & Steward, 1988) by also including resources extracted from renewable sources and ecosystems (J. Dewulf et al., 2007). The CEENE methodology counts the fossil exergy, as well as the renewable exergy invested in the product during its life cycle. The renewable exergy starts from the amount of solar irradiation necessary to grow the biomass. Together with other contributions it is then integrated in the total exergy accumulation of the product. This leads to two fractions of the total exergy content: (1) the renewable and (2) the fossil fraction. In this application, the renewable part of the analysis will not be reported. The comparison is focused on the fossil part and the corresponding emissions.

B-SAT, based on the RED Guidelines, and CEENE are not similar but remain comparable. Both start from an energy-based life cycle assessment. Both assess the relations between inputs and outputs with physical relations. CEENE and B-SAT are also capable of extending the scope of the RED-guidelines by integrating multiple types of environmental impacts. In order to interpret the exergy values, it is helpful that the HHV of biofuels and their exergy content are very similar. The difference between the two values is of the magnitude of ± 3% (Szargut, 2005). So wherever it concerns bioenergy, biofuels and bioliquids, the comparison of the differences between the B-SAT and CEENE results will resemble closely the comparison between allocation based on LHV (for B-SAT) and allocation based on HHV (for CEENE). The B-SAT and the CEENE results can thus be compared. The absolute values will not match because the primary unit is different. But the relative attribution of the energy burdens over the life cycle and the relation with the GHG-emissions should be similar. The differences between the results essentially indicate the differences in principle decisions and interpretations.

However, the B-SAT tool cannot analyse each of the legal scenarios, *i.e.* the scenarios in which certain streams are not labelled as waste, but as valuable streams. Note that the RED-guidelines are not yet fully equipped to deal with material outputs that are not destined for energy production. However, innovative uses of biomass produce co-products such as animal feedstock, valuable proteins, chemical compounds and fertilizers. The diversity is large, but these outputs cannot be labelled as waste. According to the RED-guidelines, these flows are considered as by-products and the emission impacts are related to their LHV, which is not the appropriate approach for most of these co-products as discussed above. In contrast, the CEENE methodology can account for these valuable material flows, and can analyse scenarios where uncertain streams are labelled as valuable. The approach follows the standard ISO 14041 guidelines, based on a physical relationship between the different outputs. Contrary to B-SAT, the CEENE approach is capable to analyse all four scenarios. The B-SAT is the reference, chosen for its total correspondence with the RED-guidelines. The CEENE shows similar results in the same situation, but is also capable of showing the differences when principle decisions are altered in the appraisal of waste and in the detail of the analysis. Therefore, it is chosen to use the CEENE methodology in order to be able to compare all legal scenarios from Table 18 using a case study which will be introduced in the next section.

Legally, biofuels and bioliquids can contribute to the national production quotas of renewables if their emission saving percentages surpasses the limit percentage stated in the RED-directive. B-SAT and CEENE both calculate for each output the fossil energy requirement (FER) and the corresponding GHG emissions. The FER details in MJ all fossil energy spent in the life cycle of the output. Based on this GHG emission, the emission saving percentage is determined and the acceptability of the output as a renewable fuel under the RED-directive.

4.4. Case Study - Moerdijk

The sustainability assessment will be applied on an ECP design which is comparable to the designed ECP of Moerdijk (The Netherlands). The available residues can be processed using four key conversion technologies: digestion, pyrolysis, esterification and green refinery. A schematic representation of the ECP concept is provided in Figure 24. There are two advanced processes that deliver high-value outputs. First, nature grass is valorised using a green refinery process in order to produce proteins for fodder. Secondly, various fatty residues are esterified to produce biodiesel. Both processes produce organic waste streams, *i.e.* press juices and glycerol respectively. These are added in the central digester. The two other large processes form the core of the ECP, namely the digester and the pyrolysis plant. The digester valorises manure and OMSW, but also all organic residue streams produced by all the other processes in the ECP. This results in biogas and a digestate. The biogas resulting from anaerobic digestion is further converted into Liquid Biomethane (LBM) and CO_2. The pyrolysis plant is fed with waste wood and the dried digestate. The pyrolysis plant produces bio-oil, heat and electricity. The plant provides all heat and electricity necessary for the other processes. The excess production is sold.

The structure of the ECP is highly suitable to illustrate the differences between the two sustainability assessments. First, the ECP in Moerdijk is based on multiple combined pathways, which obliges the use of allocation. Secondly, the ECP also produces biofuels and bioliquids, as well as material outputs that are not destined for energy production. Following the existing legal framework, discussed in section 4.2, all inputs and outputs are evaluated using the Waste Framework decision criteria. However, some inputs and outputs are more difficult to interpret. A categorisation of the different inputs and outputs is provided in Table 19.

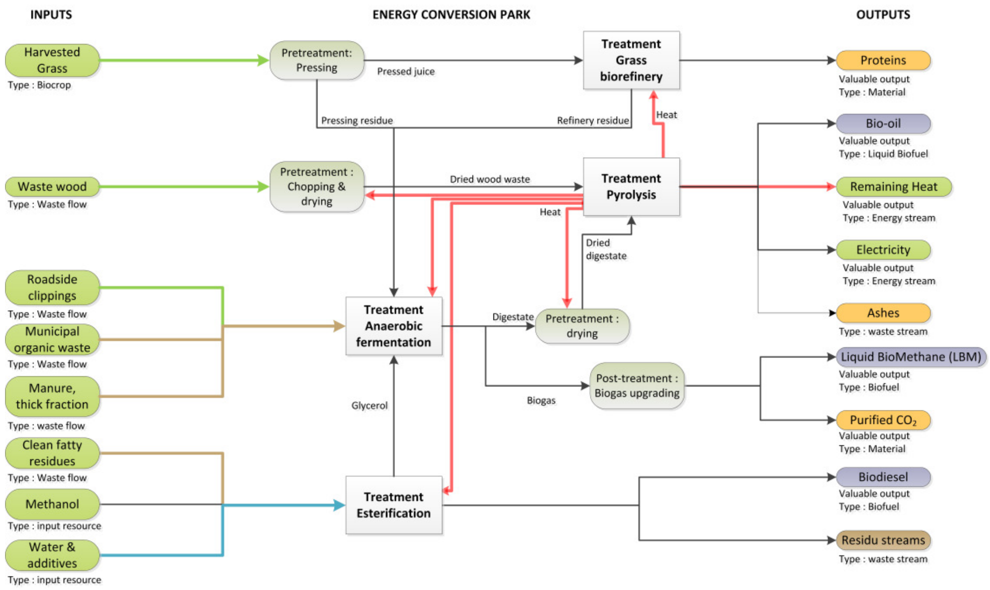


Figure 24. The ECP of Moerdijk connects different technologies to transform organic waste flows into materials

It is not always obvious if an input is characteristically waste or not. OMSW is a clear example of a waste stream. The harvested grass for the biorefinery, however, is not. It is the original idea of the ECP to collect clean grass that is a result of nature reserve maintenance. This grass can be pure waste if this maintenance is focused on the preservation of the nature reserve. However, when confronted with the active demand for clean grass, it is considered to fertilise certain areas of the reserve to a very small extent with inorganic fertilisers. This increases the grass yield significantly. But can the stream still be labelled as waste? Moreover, the set-up of the ECP keeps the option to supplement this stream with professionally grown grass on agricultural land if the reserve maintenance does not supply a sufficient quantity. The same discussion applies to the fatty residues applied for biodiesel production. These fatty residues are highly sought after, not only for biodiesel production, but also for mixing into livestock fodder. As there is an existing market for these commodities, it is no longer obvious that this waste is useless. In general, the labelling of inputs as waste is often no longer a good representation of reality.

Various organic flows can serve multiple valuable purposes. The integration of the flow in the ECP then creates market effects and substitution somewhere else.

Table 19. Overview of waste criteria for all inputs

Input	**Further use is certain**	**No processing necessary**	**Integral output of a production process**	**Further use is lawful**	**Waste?**
Clean grass	No	Yes	Yes	Yes	Uncertain[1]
Waste wood	Yes	No	Yes	Uncertain	Uncertain[2]
Roadside clippings	No	No	No	No	Waste[3]
OMSW[a]	No	No	No	No	Waste
Fatty residues	No	Yes	Yes	Uncertain	Uncertain[4]
Methanol	Yes	Yes	Yes	Yes	No waste
Water	Yes	Yes	Yes	Yes	No waste
Manure, thick fraction	Yes	Yes	Yes	Yes	No waste
H_2SO_4	Yes	Yes	Yes	Yes	No waste

[a] OMSW = Organic Municipal Solid Waste
[1] The production process is land management. Useful application of grass cuttings is uncertain.
[2] Not all types of waste wood can be reused legally
[3] Potential pollution of clippings makes reuse improbable.
[4] Both the further application and the legality of further use are not standard.

The ECP delivers different intermediate product which serve as input for other processes on the site. In the end, nine different output streams can be distinguished. Both for the intermediate products, as for the final outputs the question whether they can be classified as waste or not, has a large impact on the results of the sustainability analysis. The categorisation is shown in Table 20.

Table 20. Overview of waste criteria for all intermediate products and final outputs

Intermediate and output streams	Is commonly used for specific purposes	A market exists	Fulfils technical and legal requirements	Use will not lead to adverse impacts	Waste?
Pressing residue	No	No	No	No	Waste
Refinery residue	No	No	No	No	Waste
Digestate	Yes	No	Uncertain	Uncertain	Uncertain[1]
Glycerol	Yes	Yes	Uncertain	Uncertain	Uncertain[2]
Proteins	Yes	Yes	Yes	Yes	No waste
Bio-oil	Yes	Yes	Yes	Yes	No waste
Remaining heat	Yes	Yes	Yes	Yes	No waste
Electricity	Yes	Yes	Yes	Yes	No waste
Ashes	No	No	No	No	Waste
LBM	Yes	Yes	Yes	Yes	No waste
Purified CO_2	Yes	Yes	Yes	Yes	No waste
Biodiesel	Yes	Yes	Yes	Yes	No waste
Residual streams	No	No	No	No	Waste

[1] Digestate from manure is commonly used as fertiliser replacement, but additional renewable streams make this use uncertain.
[2] Glycerol markets exist, but the produced stream does not automatically meet all purity requirements.

Table 19 and Table 20 show that the classification of various streams according to the requirements of the Waste Framework is debatable. To illustrate the impact of this uncertainty on the sustainability assessment, scenarios BB-waste and IP-waste will regard the following inputs and outputs as waste: clean grass, waste wood, fatty residues, digestate and glycerol. Whereas, the scenarios BB-valuable and IP-valuable, will regard these streams as valuable. In these scenarios, they will be attributed a fossil energy requirement (FER) and GHG-emissions relative to their cumulative energy or exergy content built up along the production chain, *i.e.* CEENE methodology.

In the remainder of this section the results of the four legal scenarios are shown. First the sustainability assessment of the scenarios BB-waste and IP-waste using the B-SAT tool will be discussed. Secondly, the same scenarios will be discussed when evaluated using the CEENE methodology. Finally, the scenarios BB-valuable and IP-valuable will be evaluated using the CEENE methodology.

Table 21 shows the results from the analysis with the B-SAT tool. Note that with the B-SAT tool the only scenarios that can be assessed are the ones assuming that the uncertain resource streams are waste. The results show the FER and related GHG emission for each valuable output stream in two cases: analysing the entire site as one single process (BB), and the other analysing each sub-process individually (IP). RED-guidelines are followed, so material outputs that are not energy streams cannot be integrated in the calculation. This is the case for the proteins and the purified CO_2. The distribution of GHG-emissions among the three main outputs - bio-oil, LBM and biodiesel – differs strongly between the two scenarios. In the scenario B-SAT BB-waste, the interior working of the ECP is not regarded. The FER and the emissions are distributed among the resulting products pro rata of their respective weight in the RED allocation rule. In contrast, in the scenario B-SAT IP-waste each sub-process is evaluated individually. In this scenario, the bulk of the GHG-burden (63%) is attributed to the biodiesel, and the remaining part (36%) to the LBM. The bio-oil accounts for 53% of the energy content of the output, yet it only is attributed 0.4% of the FER burden and 0.6% of the GHG-emissions. It is noticeable that the bio-oil does receive a much larger part of the emission burden in the previous scenario. This can be explained by the fact that the RED-guidelines do not allocate GHG-emissions to the bio-oil from the pyrolysis plant, because the plant is fed with the dried digestate and wood waste. Note that the wood waste is mostly renewable and the dried digestate is considered a waste stream from the digester, so it has no allocated emission burden. Therefore, all corresponding emissions of the resources fed to the digester are attributed only to the LBM production. The bio-oil receives none, as in the case study it is a secondary fuel. Nevertheless, it contains a large organic energy content that is valorised through pyrolysis. Also notice that, in contrary to the BB-waste scenario, the FER burden and GHG-emissions are not equally divided over the output products in the IP-waste scenario. This can be explained by the different viewpoint in this scenario, where only the input's GHG-emissions of one specific technology are divided over its output products. Taking into account that dependent on the input product, different energy sources are used with different GHG burdens, FER burden and GHG-emissions burden are not equal. Compared to the standard fossil fuel comparator, the bio-oil shows an emission saving of 92% in the BB scenario, contrary to the 100% emission savings. On the other hand, the burden for the biodiesel and the LBM is reduced accordingly. So the emission savings realised by these outputs rise to 92% in the BB scenario compared with their standard fossil fuel comparator. The standard fossil fuel comparator is the fossil fuel that is most comparable to the renewable fuel, e.g. natural gas, diesel or crude oil.

The same scenarios are investigated with the CEENE methodology, and the results are reported in Table 22. Compared with the B-SAT results, the results from the CEENE analysis are similar, both in distributions as in range. It should be noted that the B-SAT and the CEENE tools make use of different databases and material data to feed into the calculations. A remarkable difference between these data concerns the GHG-emissions related to the OMSW fraction that is treated by the digester. Apart from this difference, noticeable in a smaller GHG-emission burden for the LBM, the results are comparable over the entire range.

Table 21. The analysis with B-SAT tool of BB-waste and IP-waste

			B-SAT BB-waste				B-SAT IP-waste		
Outputs	**Quantity**		**Net energy content**	**Fossil energy requirement**	**GHG attribution**	**Emission saving**	**Fossil energy requirement**	**GHG attribution**	**Emission saving**
			GJ/year	GJ/year	ton CO_{2eq}	%	GJ/year	ton CO_{2eq}	%
Proteins	1489	ton/year							
Bio-oil	33,945	ton/year	611,003	59,787	4321	92%	422	51	100%
Heat	62,782	GJ/year	62,782	6143	444	91%	189	23	100%
Electricity	3873	MWh/year	13,944	1364	99	96%	24	3	100%
Ashes	9012	ton/year							
LBM	174,111	GJ/year	174,111	17,037	1231	92%	26,313	2939	81%
CO_2	7185	ton/year							
Biodiesel	7768	ton/year	298,642	29,222	2112	92%	86,606	5190	81%
Waste streams	3168	ton/year							
Total			**1,160,483**	**113,554**	**8206**		**113,554**	**8206**	

Table 22. The analysis with CEENE methodology of BB-waste and IP-waste

				CEENE BB-waste			CEENE IP-waste		
			Net exergy content	**Fossil exergy requirement**	**GHG attribution**	**Emission saving**	**Fossil exergy requirement**	**GHG attribution**	**Emission saving**
Outputs	**Quantity**		GJ/year	GJ/year	ton CO_{2eq}	%	GJ/year	ton CO_{2eq}	%
Proteins	1489	ton/year	23,925	2499	159		13,118	139	
Bio-oil	33,945	ton/year	641,553	67,021	4260	92%	22,398	316	99%
Heat	62,782	GJ/year	16,832	1758	112	98%	588	8	99%
Electricity	3873	MWh/year	13,944	1457	93	97%	487	7	100%
Ashes	9012	ton/year	109	11	1		0	0	
LBM	174,111	GJ/year	191,331	19,988	1270	92%	22,843	2381	86%
CO_2	7185	ton/year	3245	339	22		387	40	
Biodiesel	7768	ton/year	304,526	31,813	2022	93%	65,989	5106	82%
Waste streams	3168	ton/year	8832	923	59		0	0	
Total			**1,204,296**	**125,809**	**7997**		**125,809**	**7997**	

The CEENE methodology is based on exergy, and can as such be applied to a larger variety of projects and products than B-SAT. The evaluation in Table 20 shows that the B-SAT calculations are only possible for the energy, biofuels and bioliquids. No GHG emission is attributed to the output materials. The valuable materials produced by the ECP are valued through CEENE and account for 2% of the total FER-burden. This small part is explained by the small exergy content of the materials in this case. Despite being highly important from an economic point of view, the materials represent only 3% of the total exergy output. So in the overall comparison of fuel sustainability this does not make a large difference in this particular case. Other projects and industrial sites may well depend much more on the production of valuable materials, and will then increasingly encounter problems to evaluate the sustainability of the bioenergy production with the RED-guidelines.

The larger applicability of the CEENE method is used here to analyse the effect of resource streams that are valuable instead of waste (*i.e.* scenarios BB-valuable and IP-valuable in Table 18). The results are illustrated in Table 23. The biggest difference with the former scenarios is the larger total quantity of GHG-emissions that are attributed to all outputs. The total rises from 8,000 ton (see Table 19 and Table 20) to 23,200 ton CO_{2eq}. Different input streams are now considered valuable materials. Waste streams only have to account for the fossil fuel expenditure and related emissions created from the moment of waste collection and transportation to the site. Valuable materials also represent FER and emissions for the creation of the material over the production chain. The fatty residues, for instance, account for 0.46 ton CO_{2eq}/ton when considered waste. These emissions reflect collection, storage and transportation to the ECP-site. When the fatty residues are categorised as valuable material, this emission factor increases to 1.85 ton CO_{2eq}/ton. The total increase of emission factors results in a total rise of emissions attributed to the outputs. The difference between the BB and the IP scenario are similar to the effects described above. The IP scenario is in principle more precise, as it regards the individual pathways of each output. If an output is linked to more energy-intensive inputs, then this will be reflected in the IP-scenarios, but not in the BB-scenarios.

Table 23. The analysis with CEENE methodology of BB-valuable and IP-valuable

				CEENE BB-valuable			CEENE IP-valuable		
			Net exergy content	Fossil exergy requirement	GHG attribution	Emission saving	Fossil exergy requirement	GHG attribution	Emission saving
Outputs	**Quantity**		GJ/year	GJ/year	ton CO_{2eq}	%	GJ/year	ton CO_{2eq}	%
Proteins	1489	ton/year	23,925	6366	462		3500	175	
Bio-oil	33,945	ton/year	641,553	170,708	12,377	78%	100,084	5528	91%
Heat	62,782	GJ/year	16,832	4479	325	93%	2626	145	89%
Electricity	3873	MWh/year	13,944	3710	269	90%	2175	120	96%
Ashes	9012	ton/year	109	29	2		17	1	
LBM	174,111	GJ/year	191,331	50,910	3691	77%	28,265	1877	89%
CO_2	7185	ton/year	3245	863	63		479	32	
Biodiesel	7768	ton/year	304,526	81,030	5875	78%	178,133	14,923	46%
Waste streams	3168	ton/year	8832	2350	170		5166	433	
Total			**1,204,296**	**320,446**	**23,233**		**320,446**	**23,233**	

The largest difference in the results can be observed with the biodiesel. In the IP-scenario, the emissions attributed to the biodiesel increase markedly. The overall emission saving, compared to the standard fossil fuel comparator, drops to 46%. This is below the acceptable level of the European directive (*i.e.* 50% from 2017 on). When these assumptions are maintained, then the biodiesel cannot contribute to the production of renewable biofuels.

4.5. Discussion and conclusion

The details of the GHG allocation according to the RED guidelines are investigated. The calculations according to RED are compared with similar calculations and allocations based on physical relations between the inputs and the outputs, as prescribed by the ISO 14041 guidelines for LCA, using the CEENE approach.

A first conceptual review of the allocation rules shows that the RED follows in general an objective physical allocation of the input burden over the output. However, on some instances this objective rule is replaced by principle decisions. First, there is the principle decision to give advantages to projects that manage to valorise low temperature heat streams. Second, the allocation is based on the LHV of the streams. This permits the methodology to move closer to energy flow valuation in the energy sector. However, this is a disproportionate advantage for gaseous fuels over liquid and solid fuels. Also, it makes it increasingly hard to incorporate non-energy streams into the guidelines in the future. Finally the RED guidelines decide principally that waste flows are not accorded any historic burden of energy or GHG emissions. The burden of waste flows integrated in the process is limited to the point of waste collection. And the waste flows produced during the process are not allocated any GHG emission. The criteria to define waste streams are being debated (Delgado et al., 2009), but are not yet integrated in the guidelines. The decision, however, has a large consequence on the burden attributed to the inputs and to the GHG emissions allocated to the outputs. For example biodiesel cannot be taken into account to attain the 20-20-20 EU targets when fatty residues are not labelled as waste. A concise review of the legal state-of-the-art on this question is therefore included, and based on the review, the resource streams of the ECP are pinpointed that show uncertainty whether to classify them as waste or not.

The effect of these decisions is illustrated by applying the calculations to a complex site of intertwined biomass transformation technologies at the Energy Conversion Park of Moerdijk (NL). Four scenarios are created and analysed: two scenarios looking at the site as a whole (BB), two looking at each subprocess separately (IP). Scenarios BB-waste and IP-waste are categorizing resources and output streams as waste if the interpretation according to legal rules is uncertain. Scenarios BB-valuable and IP-valuable regard these streams as materials with added value. A first analysis tool, B-SAT, determines the results for the scenarios BB-waste and IP-waste according to the RED guidelines. These results are compared with those obtained with the CEENE approach. This latter methodology is also capable of evaluating the scenarios BB-valuable and IP-valuable. The main differences between B-SAT and CEENE can be traced back to each of the principle differences outlined above.

The four resulting scenarios result from different legal interpretations, and the corresponding sustainability assessment yields very different results. When uncertain material streams are considered as waste, it is striking that the bio-oil from the pyrolysis plant is considered almost without any GHG burden according to the RED guidelines. The pyrolysis plant in this set-up uses an intermediary waste stream at the site itself as input. The RED guidelines divert all burdens to the LBM-production and the pyrolysis plant receives almost none. When the digestate is considered a resource of added value, however, the pyrolysis oil accounts for a large part of the fossil exergy requirement. These differences are accentuated by enlarging the view over the life cycle and by increasing the overall GHG emissions to be attributed to the outputs. In this case, a more precise calculation of the IP-scenario reveals that the biodiesel does not attain the minimum level of GHG emission savings.

It should be noted that the large differences between the scenarios are not only caused by differences in calculation, but also by principal decisions that are left for the sustainability practitioner when applying the RED guidelines to multiple pathway production processes. In accordance with other publications investigating the sustainability criteria of the RED guidelines, it can be concluded that a sustainability assessment solely based on RED does not give a large and objective view on the sustainability of the process. When using organic waste flows, the scope of the analysis over the life cycle is significantly reduced. Moreover, it is unclear how to decide when an input has to be labelled as waste. When labelling as much organic streams as possible as material with added value, the results reflect a larger view over the production chain. More GHG impacts are integrated and they can be precisely allocated to the outputs. This gives a more holistic view of the sustainability of the resulting biofuels and bioliquids. It is therefore advisable to interpret the definition of waste as narrowly as possible, as this matches the concept of cradle-to-cradle or the circular economy in which no waste exists.

The combination of multiple pathways within a production site gives rise to highly illogical results if transformation processes are combined serially, as the digester and the pyrolysis plant in this case. All burdens are attributed to the first output, whereas the second output can account for most of the energy content, but carries no GHG emission burden. The RED-guidelines advise to consider biorefineries as a black box and avoid allocation between the different conversion processes. But this approach is hard to maintain if subprocesses at the site are from different owners, as is often the case in an industrial ecology set-up. Moreover, the analysis focusing on individual processes reveals much closer the real impact of each product. Therefore, this black-box approach is a severe limitation to the application of the RED-guidelines when confronted with complex production sites. In its current form, the RED-guidelines are not developed with such complex biorefineries in mind. This is also revealed by the allocation rules based on the lower heating value, which is not applicable to many materials. A modification to the analysis based on an exergy value would broaden significantly the range of potential applications, covering many innovative processes as well. Finally, the focus of the RED on the GHG emissions only, does not regard the need to use and transform renewable sources efficiently. Highly efficient processes, using partly fossil resources, have a significant disadvantage as a result of this single-sided point of view.

In general, it can be concluded that the guidelines provided by the RED are based on practical decisions rather than objective sustainability criteria. With the guidelines in their current form, it can be advised to combine sustainability assessments based on the RED guidelines with other more holistic assessments in order to obtain a more precise view on the sustainability of the project. The guidelines still need to be brought in accordance with the concept of resource efficiency which is implemented by the European Union and which is followed by the 2012 Commission's strategy and action plan 'Innovating for Sustainable Growth: a Bio-economy for Europe' in which focus is put on materials, rather than energy.

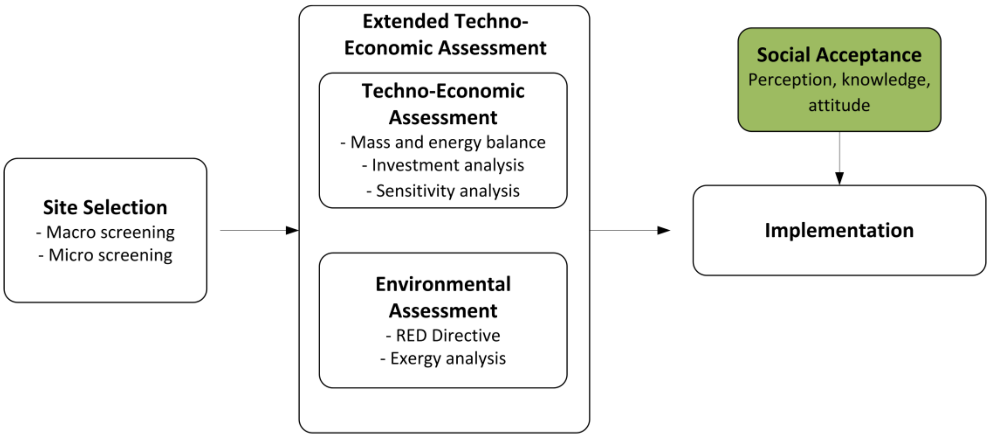
Chapter 5.

Social Acceptance

Perception – Knowledge – Attitude*

* *Parts of this section have been submitted:*
Van Dael, M., Van Passel, S., Leroi-Werelds, S., and Swinnen, G. (2014) Biomass hot or not? Social acceptance of bioenergy in Belgium. Submitted.

In this chapter the last subquestion of this dissertation will be answered, *i.e.* what is the knowledge, perception and attitude concerning biomass? Taking into account that (1) young citizens' knowledge and perceptions of bioenergy are important for future policy makers and (2) that experience has shown that children and young citizens are instrumental in achieving long-term behavioral changes in the use of renewable energy sources, this study is focused on young citizens having reached an age between the ages 16 and 25.



5.1. Introduction

5.1.1. Literature overview

Many barriers that hinder the successful implementation of energy projects can be considered to result from a lack of social acceptance (Qu et al., 2011). Sustainable energy initiatives cannot be implemented without sufficient public support. Therefore, it is important to understand how public acceptability develops and how it can be changed (Perlaviciute & Steg, 2014). This research question is also important for policy makers as the success of policies is dependent on public support, which is often driven by perceptions (Truelove, 2012). For that reason, an overview will be provided of theoretical models suggested by scholars in order to better understand the relationship between knowledge, perception, attitude (strength), intentions, and behavior.

In the remainder of this chapter, attitude strength, intentions and behavior will be defined as follows. Attitude strength is the degree to which an attitude is resistant to change and influences information processing and behavior. Intention to behave is the determination to act in a certain way. Finally, behavior is defined as the way in which a person behaves or acts.

One explanation for the low level of public acceptance might be the fact that the general level of knowledge concerning renewable energy is low. Indeed, it is often assumed that the more knowledgeable people are on a subject, the more positive their attitudes are (Qu et al., 2011). For example, Gossling et al. (2005) show that the level of knowledge concerning (renewable) energy among students in Germany is low and that a general distrust exists due to environmental catastrophes, scandals and dishonesty. Kapassa, Abeliotis, and Scoullos (2013) conclude from their study that the knowledge of students concerning green chemistry is low and that education and training is needed if a widespread use of renewable feedstocks in everyday life is desired. Also, Sudarmadi et al. (2001) indicate that education must provide information so that people can adapt to changing environmental circumstances. Many of these aforementioned studies are based on the assumption that more knowledge will lead to more positive attitudes and behavior. This assumption is based on the information deficit model[1] of public understanding and action (Burgess, Harrison, & Filius, 1998) and is proven to be partly wrong (Kollmuss & Agyeman, 2002). Indeed, Simcock et al. (2014) and Perlaviciute and Steg (2014) argue that information provision is not by definition a synonym for an increased knowledge level and, for that reason, it is important to know whether information is received and perceived by people in the way it is designed to reach them. Information provision can extend people’s knowledge level or correct for misperceptions. However, they note that the way in which knowledge influences acceptability, also depends on contextual and general psychological factors. Similarly, Devine-Wright (2007) notes that there is little evidence that more

[1] The model attributes public skepticism toward environmental issues to a lack of knowledge and assumes that providing more information will overcome this lack of knowledge. According to the theory, communication should focus on improving the transfer of information from experts (*i.e.* people having the information) to non-experts.

informed individuals are more receptive of renewable energy technologies. In many cases a single approach, such as the provision of more information is not sufficient to encourage meaningful levels of behavioral change. Therefore, it is argued to use multiple strategies in order to target a wider audience and to increase adoption levels (Yohanis, 2012).

Different ways to explore the impact of the transfer of information on knowledge, perception, attitude (strength), intentions and behavior exist. Hobman and Ashworth (2013) investigate the influence of information provision, concerning costs and emissions of technologies, on public support within the questionnaire itself. Similarly, Dowd, Itaoka, Ashworth, Saito, and de Best-Waldhober (2014) provide information on the scientific characteristics of CO_2 within the questionnaire to check the influence on the opinion formation on carbon capture and storage (CCS) implementation. Hobman and Ashworth (2013) also found studies that use other methodologies to transfer information, such as information choice questionnaires[2], workshops or group interactive processes. Moreover, information can be provided using a lecture, a site visit or web-related tools such as an informative website or social media (Baird & Fisher, 2005).

One of the most influential attitude-behavior models is the Theory of Planned Behavior (Kollmuss & Agyeman, 2002). The model results from the Theory of Reasoned action which was first developed by Ajzen and Fishbein (1980). In the latter model the authors assumed that behavior is voluntary. Since this is not entirely correct, the authors later added perceived behavioral control and named the new model the Theory of Planned Behavior. In this model a relationship is described between attitude, subjective norms and perceived behavioral control which influence intention which, in turn, has an impact on behavior (Ajzen, 1991). Important in this model is that a high correlation between intention and

[2] Choice questionnaires are used to collect informed public opinions. The questionnaire provides information about the different options from which the respondent can choose, as well as the consequences of the options. Furthermore, it contains a procedure designed to assist respondents in processing the information and making their choice (Neijens, De Ridder, & Saris, 1992).

behavior can only be found when the intention is measured to a specific behavior. For example Nameghi and Shadi (2013) investigate the relationship between consumer attitude and intention to practice green (*i.e.* reducing, recycling, and reusing). Polonsky, Vocino, Grau, Garma, and Ferdous (2012) base their research on the Theory of Reasoned Action, adding knowledge to the model. The authors make a distinction between general and specific knowledge and conclude that both have an influence on environmental attitudes. Both the Theory of Reasoned Action and the Theory of Planned Behavior assume that pre-stored beliefs will be activated. However, when dealing with novel objects, these beliefs do not exist yet. Therefore, attitudes for these novel objects are created directly, based on information that is available at that very moment (*i.e.* the context). In other words, the influence of the context will be high. For example, if respondents are first provided information on fossil fuels, the provided answers will differ from the answers when first provided a lesson concerning renewable energy. van den Hoogen (2007) shows that, for biomass perception, the contextual influence is higher when attitudes are weak. In his research, attitude strength is investigated as an antecedent of attitude itself. The author argues that knowledge is one of the antecedents of attitude strength. The strength itself is determined by the following indicators: ambivalence, importance, consistency, certainty, intensity, extremity and accessibility. When the attitude strength is higher, the influence of the context will be lower.

Rajecki (1982) tries to explain the gap between attitude and behavior and points out that direct experiences have a stronger effect on behavior than indirect experiences such as learning at school. The author also points to the influence of cultural traditions, norms and family customs, as well as the fact that people's attitudes change over time.

From the review of Kollmuss and Agyeman (2002) the authors conclude that gender and years of education have an influence on environmental attitude and behavior. Women generally have a lower level of knowledge concerning the environment, but are more concerned and are more willing to change. Furthermore, Kollmuss and Agyeman (2002) note that the knowledge level increases when education is longer. However, as the authors indicate, more education does not necessarily lead to a more positive attitude towards the environment.

Taking the above information and models into account, the present research aims to investigate how factual knowledge, perception, attitude strength and attitude concerning bioenergy are related. Factual knowledge about renewable energy is used to check what consumers really know about renewable energy. Perceptions concerning bioenergy are defined as the knowledge concerning bioenergy that respondents believe to be correct. In the first hypothesis it is assumed that providing a lesson, will increase the knowledge of respondents (H1). Then, it is hypothesized that more knowledgeable respondents will have more positive perceptions concerning bioenergy (H2). In this model attitude-related items are defined in the form of behavioral intentions (*i.e.* 'Intention to Use' (ITU) and 'Intention to Learn' (ITL)), which are distinct from actual behavior. It is assumed that respondents with a more positive perception have a higher 'Intention to Use' (H3) and 'Intention to Learn' (H4) about bioenergy. Furthermore, it is assumed that 'Attitude strength' behaves as a mediator between 'Perception' and 'Intention to Use' (H5) and 'Intention to Learn' (H6). Discussions about the nature of the link between behavioral intentions and actual behavior are still ongoing (Barber, Taylor, & Strick, 2009; Davies, Foxall, & Pallister, 2002), and not taken into account in this research. A schematic overview of the proposed path model is provided in Figure 25.

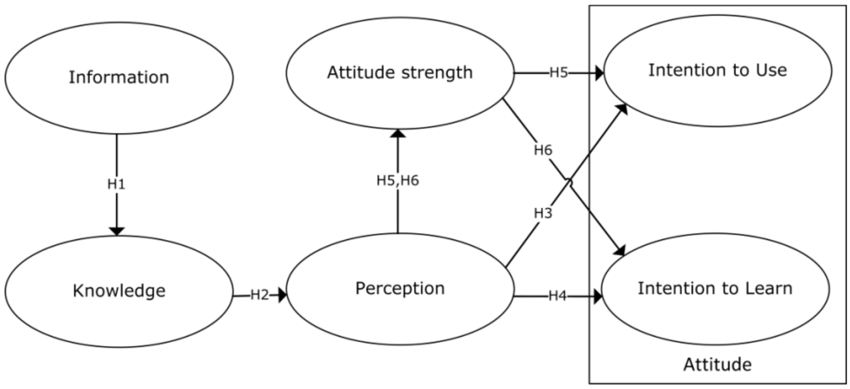


Figure 25. Path model of knowledge, perception and attitude

The influence of informed respondents on Intention to Use and Intention to Learn is investigated by providing a lecture. The lecture exists of two parts. First, some general information concerning sustainability and the sources of renewable energy is provided. Further, the current share of renewable energy and bioenergy is described and advantages and disadvantages of renewable energy are discussed. In the second part more detailed information concerning bioenergy is provided: the sources of bioenergy, processing technologies, advantages and disadvantages. The lecture takes approximately 30 minutes and is given by the same person in order to provide all students with exactly the same information. Although indicated by Rajecki (1982) that indirect experience does not have a large influence on behavior, a lecture is indicated as the preferred methodology, in this study, for information transfer as the setting can be fully controlled by the researcher. In case of web-related tools the researcher cannot control whether the respondents are disturbed while using the tool or whether respondents look at all information. Providing the information on the questionnaire itself would also be possible as the researcher can be sure that all respondents receive exactly the same amount of information and in exactly the same format. However, taking into account the amount of information, it would take too long and chances are high that respondents would not read all information provided. Furthermore, a traditional class-room lecture is still the most used teaching-manner in Belgium and, therefore, most familiar to the respondents.

5.1.2. Data and context

The study is performed in the province of Limburg (Eastern part of Belgium). Limburg is a green province (*i.e.* many forests are present) compared to other Flemish provinces. Despite the great interest in renewable energy, bioenergy initiatives face local protest, especially when the installation is planned close to a residential area. At Hasselt University (situated in the province of Limburg) it is noticed that especially bachelor students have a rather low awareness of biomass. This is not a surprise given that in the current curriculum of secondary schools there seems to be little room for teaching students about renewable energy. Furthermore, the topic of renewable energy is taught in the class of geography, and not nature sciences as would be expected. Based on information from different secondary schools it seems that often solely one lecture of *ca.* 50 minutes can be spent on energy-related topics, implying that teachers can only very briefly discuss renewable energy forms. As a consequence, often only solar and wind energy (which are the most familiar renewable energy sources in Belgium) are covered. However, some schools spend more attention to renewable energy by choosing the theme for the course 'seminar' (*i.e.* time that a school can fill in freely with self-selected topics). Seminars with a scientific theme such as renewable energy are mainly chosen by pupils that take scientific courses and not by pupils in e.g. humanities. These findings might be of concern as renewable energy is a societal problem that should gain sufficient attention in various disciplines. For this reason, a survey study was performed between December 2013 and March 2014 aiming to identify the factual knowledge, perception, attitude strength and attitude (*i.e.* ITU and ITL) of students towards bioenergy. Next to the bachelor students of the university, the survey is also taken from students in the fifth and sixth grade of six different secondary schools all over the province. In total, the survey is completed by 715 students of which 281 received a lecture. An overview of the respondents can be found in Table 24.

Table 24. Overview respondents

	Secondary school*		**University**	
	Male	Female	Male	Female
Lecture	81	75	63	62
No lecture	64	100	152	118

* List of schools:
Sint-Augustinus Instituut Bree (n = 37)
Martinusschool Bilzen (n = 27)
Sint Michiel Leopoldsburg (n = 75)
Atheneum Plus Hasselt (n = 129)
Scholen Kindsheid Jesu Hasselt (n = 34)
Spectrumcollege bovenbouw Sint Jozef Beringen (n = 18)

5.2. Methodology

The questionnaire consists of four different parts that aim to assess: (1) knowledge, (2) perception, (3) attitude and (4) socio-demographics. The questionnaire is to a large part based on previous work from Halder, Pietarinen, Havu-Nuutinen, and Pelkonen (2010) (*i.e.* questions 1.10, 2.1 (1), 2.1 (2), 2.1 (4), 2.1 (5), 2.2 (1), 2.2 (2), 2.2 (5), 3.1 (1-6), and 3.2 (1)), Zyadin, Puhakka, Ahponen, Cronberg, and Pelkonen (2012) (*i.e.* questions 1.1, 1.8, and 1.9), and Goorix and Meijnders (2003) (*i.e.* questions 3.5 - 3.9) and was slightly changed to fit the situation in Belgium. For example, some questions were added concerning biomass residues streams as it is believed that this source will gain importance in Belgium. In the study of Halder, Pietarinen, Havu-Nuutinen, and Pelkonen (2010) no questions were available concerning attitude strength. To this end the study of Goorix and Meijnders (2003) was used. Also, the study of Halder et al. (2010) contained open-ended questions to measure the knowledge level of respondents. To avoid the difficulties going side by side with open-ended questions, we chose to use the closed-type questions from the study of Zyadin et al. (2012). The questionnaire consists of closed-type questions, mainly seven-point Likert-type scale questions (Totally disagree - Totally agree) supplemented with the option 'I don't know' (see Appendix 4). After the questions measuring knowledge, a clear definition is provided of biomass and bioenergy. The data is collected anonymously. It takes approximately 15 minutes for the respondents to fill out the questionnaire. Students with and without a lecture receive the same questionnaire. Students that are provided a lecture fill out the questionnaire immediately after they receive the lecture. Questions can only be asked after the survey is completed. Moreover, the teacher makes sure that no opinion is given for or against bioenergy or another renewable energy source. Furthermore, the lecture is first discussed with different teachers to make sure the level matched the level of the students.

The data is analyzed using the statistical software program IBM SPSS version 22.0 and smartPLS 2.0. Simple descriptive statistics as well as different non-parametric methods are used in order to find out the respondents' knowledge, perception and attitude regarding bioenergy. A factor analysis is performed to identify the different underlying dimensions related to bioenergy perception and attitude amongst the students. Furthermore, using structural equation modelling (SEM) the underlying relationship between knowledge, perception, attitude strength and attitude are investigated. This methodology allows estimating the measurement and structural model at the same time and allows accounting for measurement error (Polonsky et al., 2012). It is chosen to use the PLS-method (partial least squares) for several reasons: (1) the model contains formative as well as reflective measurement items which can easily be analyzed by PLS, (2) PLS avoids a distributional pattern assumption for the observations for which there is a need to be independently distributed, (3) a side benefit of the partial nature of the PLS algorithm is that sample size requirements are smaller than required for covariance based methods, (4) PLS allows estimating higher order models, and (5) PLS works better for complex models, *i.e.* when the focus is on the interrelationships among a large set of factors and in case of many manifest variables (Chin, 2010; Chin & Newsted, 1999).

In the remainder of this section a distinction will be made between pupils and students. Pupils are the respondents from the fifth and sixth grade of secondary school, whereas with students we mean the respondents from the university.

5.3. Results

5.3.1. Respondents' knowledge about renewable energy

In the first part of the questionnaire, respondents' general knowledge of renewable energy is tested through a series of closed questions. When processing the results of these questions, all respondents are categorized into one of seven knowledge levels from very low to very high. The questions in the first part of the questionnaire and the method of categorizing them can be found in Appendix 5.

From the results it is revealed that young people, that are not instructed, are most familiar with wind, water, and the sun as renewable energy sources. Wind and solar energy infrastructure are also most visible in the landscape of Belgium, which can partly explain the high awareness. However, for water energy this is not the case, as it is barely available in Flanders. It is striking that solar energy is less frequently recognized as a source of renewable energy in comparison with wind and water. The authors believe this may be due to the information that has appeared in the media with many discussions dealing with the (unfair) subsidies for solar energy. Biomass and geothermal energy are less known by the students. However, more than half of the students still recognize these sources as being renewable. At secondary schools, only 50% (respectively 33%) of the pupils recognize bioenergy (and geothermal energy) as a renewable energy source. It is remarkable that 18% of the pupils respond that nuclear energy is a source of renewable energy. Also, 16% indicate oil to be renewable and 8% indicate natural gas and coal to be renewable energy sources. This may be due to the fact that some pupils do not know what 'renewable' means. The results differ if a lecture is given. In this situation, most of the students and pupils are able to indicate the proper renewable energy sources. More than 95% of the students and pupils correctly recognize wind, water, bio- and solar energy. Geothermal energy is recognized by fewer students (84%) and pupils (76%). An unexpected response is obtained for shale gas. More students and pupils answered shale gas to be renewable after a lecture is provided. However, shale gas is not mentioned during the lecture.

Based on the Mann-Whitney U test, male respondents have a significantly higher knowledge than female respondents when no lecture is provided. After providing a lecture about renewable energy, no significant differences can be found in the level of knowledge based on gender. The initial knowledge (*i.e.* knowledge level between rather high and very high before receiving a lecture) is higher for students (43.3%) than for pupils (24.3%). However, pupils and students did a fairly good job in providing the correct answers after receiving a lecture. After receiving the lecture, 74% of the pupils have a high to very high score in comparison to 69% of students. This slight difference is not significant.

5.3.2. Respondents' perception about bioenergy

In the second section of the questionnaire several statements are provided to the respondent to analyze the perception one had about bioenergy. An overview of the responses can be found in Table 25.

Table 25. Perception – Frequencies and agreement index (%)

Statement	TD[1]	D[2]	RD[3]	NDNA[4]	RA[5]	A[6]	TA[7]	DKn[8]	AI[9]
An increase in the use of bioenergy can help reduce the greenhouse gas effect.	0.7	1.7	4.9	9.1	22.5	41.7	16.5	2.9	73.4
Bioenergy can replace the use of fossil fuels in the future.	0.8	4.3	9.7	12.4	25.6	34.3	9.8	3.1	54.9
Bioenergy will be the main source of energy in Belgium in the future.	1.3	5.6	16.6	22.2	24.6	17.2	5.9	6.6	24.2
An increase in bioenergy can lead to a drop in food production.	6.4	16.2	23.8	17.5	10.5	6.7	3.2	15.7	-26
Wood will be one of the main sources of bioenergy in Belgium in the future.	5	15.1	25.7	20.1	14.7	7.8	0.8	11	-22.5
Production of energy from wood is environmentally friendly.	6.3	18.7	27.1	17.6	15.1	9.1	1.8	4.2	-26.1
The felling of trees for energy production is justified when the same amount of trees is being replanted.	2.4	9.5	16.5	15.7	22.7	20.7	11.5	1.1	26.5
Production of energy from biomass waste such as manure, organic municipal solid waste or clippings is environmentally friendly.	0.7	2.4	7	10.9	32	30.3	10.5	6.2	62.7

Waste streams such as manure, organic municipal solid waste or clippings will be one of the main sources for energy in Belgium in the future.	1.3	4.3	14.5	24.8	22.4	16.4	3.5	12.9	22.2
The government should support research and development of bioenergy.	0.3	0.3	2	8.1	20.4	37.8	28.3	2.9	83.9

[1] TD = Totally disagree
[2] D = Disagree
[3] RD = Rather disagree
[4] NDNA = Neither disagree, nor agree
[5] RA = Rather agree
[6] A = Agree
[7] TA = Totally agree
[8] DKn = I don't know
[9] AI = Agreement index (percentage agreeing *minus* percentage disagreeing)

Most of the respondents agree that an increase in the use of bioenergy can help to reduce the greenhouse gas effect and replace fossil fuels. Also, almost all respondents agree that the government should provide support for research and development of bioenergy. However, a significant difference can be found, based on the Mann-Whitney U-test, between respondents that are provided a lecture and those that are not. Respondents that are not provided a lecture, are more negative about bioenergy being able to reduce the greenhouse gas effect and about the government having to provide support for research and development of bioenergy. This may be due to the fact that many respondents, who receive no prior lecture, are unaware of biomass being a source of renewable energy.

The majority of the respondents does not perceive wood as being environmentally friendly and does not perceive it as being one of the main sources of bioenergy in the future for Belgium. The respondents indicate that the use of wood for energy production might be justified if the same amount of wood is replanted. The majority of the respondents perceive the use of waste streams as being more environmentally friendly and being an important source for renewable energy in the future. This is an interesting finding taking into account that waste streams will gain increasing attention in the framework of the biobased economy in which cascading principles will be of major importance (Van Dael, Márquez, et al., 2013). Cascading implies that biomass sources will first be used at their highest value, being chemicals, food or feed and only when no other usages are feasible, energy will become an option.

Respondents have different beliefs concerning the question whether an increase in bioenergy can lead to a drop in food production. Seeing the complexity and diversity of biomass sources it is no surprise that respondents, who are not so familiar with the topic, cannot provide a clear answer to this question.

Based on a Mann-Whitney U test and Kolmogorov-Smirnov test it can be concluded that there is a significant difference in the responses of male and female respondents. Females are at this moment more positive towards bioenergy than male respondents. This contradicts to the findings of Halder et al. (2010), since in their study, boys are more positive than girls. Whereas it confirms the findings of Kollmuss and Agyeman (2002) and Zyadin et al. (2012). Moreover, the respondents that are provided a lecture, perceive the future role of bioenergy to be larger than those respondents that aren’t provided a lecture before completing the questionnaire. This might be explained by the increased awareness of biomass being a source of renewable energy. Furthermore, pupils have a significantly more positive view of the future of bioenergy than university students. This might be explained by the fact that students are more critical based on their general knowledge level and are more influenced by mass media. No significant difference can be found based on the educational degree of the mother and father of the respondents.

A Kruskal-Wallis test is performed to check for significant differences based on the level of knowledge and course program of the respondents. The level of knowledge seems to have little influence on the perception of bioenergy. Significant differences can be found between students following a scientific program and students following an economic program at the university. Students following a scientific program seem to be more negative towards the use of biomass as a source of energy. However, part of the economic students received a lecture, whereas none of the students following a scientific program received a lecture. Therefore, the significant difference might be explained by the provision of a lecture instead of the difference in course program. If we correct for this by running a two-way ANOVA test, we didn't find any significant results for the interaction term between lecture and course program. If we only compare those students following an economic program that didn't receive a lecture and the students following a scientific program, the significant difference disappears.

5.3.3. Respondents' attitudes towards bioenergy

The third section of the questionnaire contains different statements concerning the attitude of the respondents towards bioenergy. An overview of the responses can be found in Table 26. The questions can be divided into two groups: (1) intentions to use (ITU) and (2) intentions to learn (ITL).

Respondents are relatively positive towards the future use of bioenergy as a transport fuel or as energy source in their house. However, if the price of the bioenergy is higher than alternative energy sources, the ITU bioenergy decreases drastically. Contrary to the relatively positive ITU, the respondents are rather negative towards the ITL more about bioenergy. When respondents are asked whether they would like to learn more about bioenergy, they respond positively. However, the questions, whether they would like to discuss the topic with their teachers, friends or parents and whether they would like to visit a bioenergy plant, are responded negatively to. In particular pupils seem to have a significantly lower ITL than students from the university. Also, respondents that are provided a lecture, have a lower ITL. The reason for this lower ITL for respondents that are provided a lecture might be explained by the format of the lecture. Taking into account the consistency, which is necessary to draw statistical meaningful conclusions from the data, the lecture has to be exactly the same for every group. Therefore, a powerpoint presentation of 30 minutes is used, which may be perceived as being rather boring for the respondents. Creative ways to inform young people about bioenergy have to be searched for.

Table 26. Attitude – Frequencies and agreement index (%)

Statement	**TD**[1]	**D**[2]	**RD**[3]	**NDNA**[4]	**RA**[5]	**A**[6]	**TA**[7]	**DKn**[8]	**AI**[9]
In the future I would like to drive a car on bio-fuel (e.g. biomethane or biodiesel).[10]	3.4	3.8	6.3	21.8	22.4	27.7	9.1	5.6	45.7
I would like to visit a bioenergy plant in my region.[11]	7.1	14.8	16.6	24.8	17.6	13.1	3.9	2	-3.9
I would like to learn more about bioenergy in the future.[11]	4.3	7.3	9.1	21.7	29.9	21	5.5	1.3	35.7
I would like to discuss bioenergy with my teachers.[11]	9.4	17.8	16.6	25.2	16.4	8.7	4.1	2	-14.6
I would like to discuss bioenergy with my parents.[11]	14.4	19.2	17.3	24.3	15.2	5.5	2.5	1.5	-27.7
I would like to discuss bioenergy with my classmates.[11]	13.8	17.8	14.1	26	16.4	8.3	2.2	1.4	-18.8
I'm environmentally conscious.	2.5	3.5	11.2	25.2	33	17.2	4.9	2.5	37.9
In the future I would like to use bioenergy in my house.[10]	1.4	1.7	2.4	16.6	32.7	29	10.5	5.7	66.7
I would buy bioenergy.[10]	1.7	1.5	3.6	19.6	35	24.9	6.7	7	59.8
I would buy bioenergy for my energy supply, even if it would cost more.[10]	5.6	9	20.1	27	19.3	8.1	3.5	7.4	-3.8

[1] TD = Totally disagree
[2] D = Disagree
[3] RD = Rather disagree
[4] NDNA = Neither disagree, nor agree
[5] RA = Rather agree
[6] A = Agree
[7] TA = Totally agree
[8] DKn = I don’t know
[9] AI = Agreement index (percentage agreeing *minus* percentage disagreeing)
[10] ITU, [11] ITL

The respondents that are provided a lecture also indicated to be (significantly) less environmentally conscious. Moreover, from the results it can be concluded that females are less willing to learn about bioenergy, however, their ITU bioenergy in the future is significantly higher. Taking into account that females are more positive towards bioenergy, it might not come as a surprise that their ITU bioenergy is higher. This finding contradicts the findings of Zyadin et al. (2012) who find no significant gender difference for attitude-related items.

A Kruskal-Wallis test indicates significant differences if no lecture is provided, based on the education of the father. If the father has a higher degree, respondents are more willing to discuss the topic at home and are willing to pay more for bioenergy.

5.3.4. Underlying dimensions of perception and attitude

Both perception and attitude-related items are combined to perform a factor analysis. For this analysis all respondents that answered 'I don't know' on one of the statements are treated as having a missing value. For missing values we use a pairwise deletion (*i.e.* removing the specific missing values and not the entire case). The analysis reveals five principal components when using the Kaiser criterion implying an eigenvalue greater than one. When the analysis is performed for the perception and attitude-related items separately, the same underlying dimensions are found. However, scholars have already indicated that the Kaiser criterion typically overestimates the number of components (Zwick & Velicer, 1986) and that the parallel analysis is the preferred estimate to determine the number of factors to retain (Hayton, Allen, & Scarpello, 2004). In the parallel analysis the number of components are determined by extracting eigenvalues from a number (*i.e.* 1000 in this research) of random data sets that parallel the actual data set with regard to the number of cases and variables (O'connor, 2000). The rationale is that the components from the real data set should have larger eigenvalues than the components derived from the random data set. In this dissertation we use the SPSS commands prescribed by O'connor (2000) to perform this analysis. If all perception and attitude-related items are combined, the analysis indicates that four components should be retained.

However, if we perform the analysis separately for the perception and attitude-related items, we find that for the perception related items three components have to be retained and for the attitude-related items two components. Taking the above results into account, it is chosen to extract the components for the different concepts separately. In that case, the retrieved components explain 55.66% of the total variance in the students' perception and 68.19% of the total variance in the students' attitude towards biomass. The literature varies on how much variance should be explained before the number of factors is sufficient. Some indicate that 50% is acceptable, other suggest 75% to 90% should be accounted for (Beavers et al., 2013). Table 27 and Table 28 provide an overview of the results of the analysis for respectively the perception-related and attitude-related items. The questions related to the respondents' perception, are divided into three different components or factors: (1) The future role of bioenergy, (2) the role of wood as a source of bioenergy, and (3) the sustainability aspects of bioenergy. These results differ from the findings of Halder et al. (2010) since the questions in our study are supplemented with questions concerning waste products. This is opted for as the interest in waste streams, in the future, will probably be higher than the interest in wood as a source of energy in Belgium. Our results also indicate that questions related to the use of wood for bioenergy are combined in one factor, indicating that respondents treat this biomass source separately from all other sources. For the attitude-related items two factors are found. The first factor is 'intention to learn' (ITL) which can be compared with the factor 'motivation' in the study of Halder et al. (2010). The second factor is 'intention to use' (ITU) which can be compared with 'utilization' in the previously mentioned study.

Table 27. Factor analysis of students' perception about bioenergy[1,2]

Statement	Factor 1[a]	Factor 2[b]	Factor 3[c]
Bioenergy will be the main source of energy in Belgium in the future.	**0.833**	0.204	0.028
Bioenergy can replace the use of fossil fuels in the future.	**0.749**	-0.130	0.131
Waste streams such as manure, organic municipal solid waste or clippings will be one of the main sources for energy in Belgium in the future.	**0.540**	0.308	0.232
Production of energy from wood is environmentally friendly.	-0.080	**0.752**	0.170
Wood will be one of the main sources of bioenergy in Belgium in the future.	0.289	**0.732**	-0.207
The felling of trees for energy production is justified when the same amount of trees is being replanted.	0.071	**0.610**	0.172
Production of energy from biomass waste such as manure, organic municipal solid waste or clippings is environmentally friendly.	-0.014	0.142	**0.766**
An increase in the use of bioenergy can help reduce the greenhouse gas effect.	0.100	0.110	**0.665**
The government should support research and development of bioenergy.	0.343	-0.067	**0.612**

[1] Rotated components using varimax.
[2] Kaiser-Myer-Olkin measure of sampling adequacy = 0.661
[a] Future role of bioenergy
[b] Role of wood for bioenergy
[c] Sustainability of bioenergy

Table 28. Factor analysis of students' attitude towards bioenergy[1,2]

Statement	Intention to learn	Intention to use
I would like to discuss bioenergy with my classmates.	**0.841**	0.141
I would like to discuss bioenergy with my parents.	**0.839**	0.139
I would like to discuss bioenergy with my teachers.	**0.833**	0.157
I would like to learn more about bioenergy in the future.	**0.766**	0.299
I would like to visit a bioenergy plant in my region.	**0.716**	0.222
I would buy bioenergy.	0.187	**0.857**
In the future I would like to use bioenergy in my house.	0.227	**0.845**
In the future I would like to drive a car on bio-fuel (e.g. biomethane or biodiesel).	0.108	**0.784**
I would buy bioenergy for my energy supply, even if it would cost more.	0.229	**0.720**

[1] Rotated components using varimax.
[2] Kaiser-Myer-Olkin measure of sampling adequacy = 0.863

5.3.5. Estimation of the path model linking knowledge, perception and attitude

In the following step structural equation modeling (SEM) is performed in smartPLS 2.0. The goal of this analysis is to better understand the relationship between the different latent variables (*i.e.* unobservable variables or constructs) as described in Figure 25. SEM allows to simultaneously estimate the structural and measurement model. The structural model describes the relationships between the latent variables, whereas the measurement model describes the relationships between the indicators and the latent variables. The indicators measure the latent variables.

The latent variables 'Information', 'Knowledge', 'Perception' and 'Attitude strength' are assumed to be formative, whereas the latent variables 'Intention to Use' and 'Intention to Learn' are defined as being reflective. It is crucial to correctly define the relationship between the construct and its indicators in order to avoid biased parameter and standard error estimates for the structural model and inflated type II errors (MacKenzie, Podsakoff, & Jarvis, 2005). Formative indicators are multidimensional in nature (*i.e.* a change in one indicator is not necessarily associated with a change in another indicator of that construct), whereas reflective indicators are unidimensional and thus highly correlated. An overview of the characteristics of reflective and formative constructs is provided by Jarvis, MacKenzie, and Podsakoff (2003).

An overview of the detailed structural equation model is provided in Figure 26. Missing values are treated by mean replacement. The indicators are labeled with the question number as shown in Appendix 4. Perception is measured as a second-order model consisting of the three sub-dimensions that resulted from factor analysis (see section 5.3.4). The sub-dimensions are labeled 'Factor 1', 'Factor 2', and 'Factor 3' and are respectively defined as (1) The future role of bioenergy; (2) the role of wood as a source of bioenergy, and (3) the sustainability aspects of bioenergy (*cfr.* the factors in the previous section). For estimation a two-step procedure is used. At the first step, the complete model is estimated with 'Perception' defined by all the indicators describing the three factors. The resulting latent variable scores for the three factors are used in a second step as formative indicators for the 'Perception' construct. 'Attitude strength' is measured using questions 3.5 – 3.9 (*i.e.* certainty, importance, involvement and ambivalence). For the questions related to ambivalence, the same procedure as for 'Perception' is used to combine them in one latent variable score. The resulting latent variable score is called 'Ambivalence'. The results of the structural equation model are provided in Figure 27.

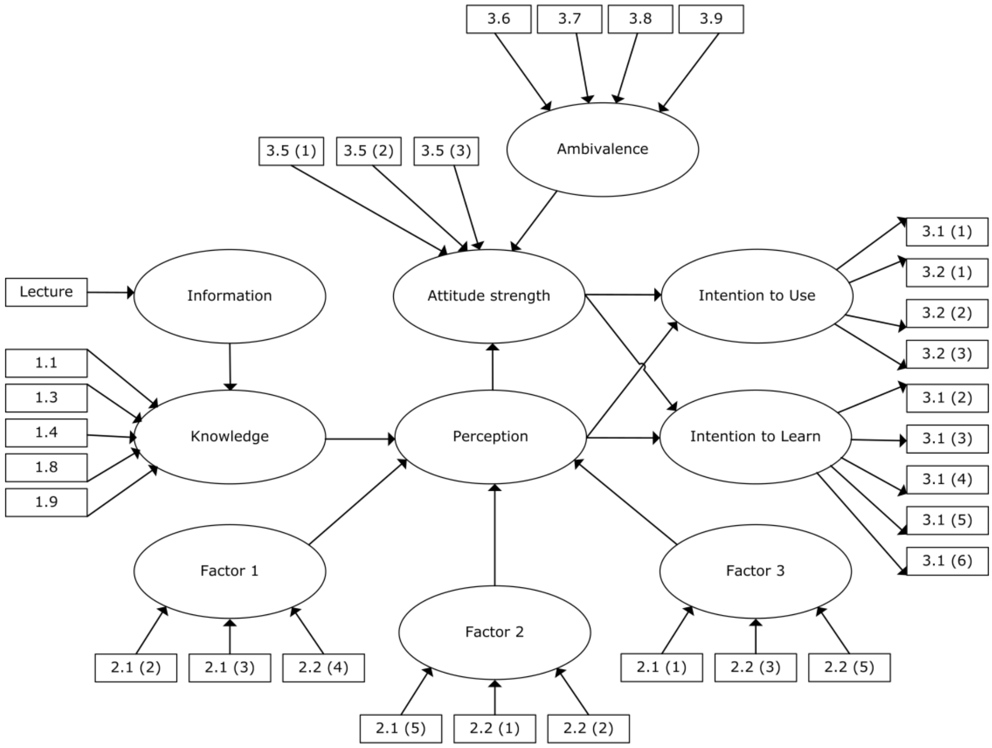


Figure 26. Structural equation model

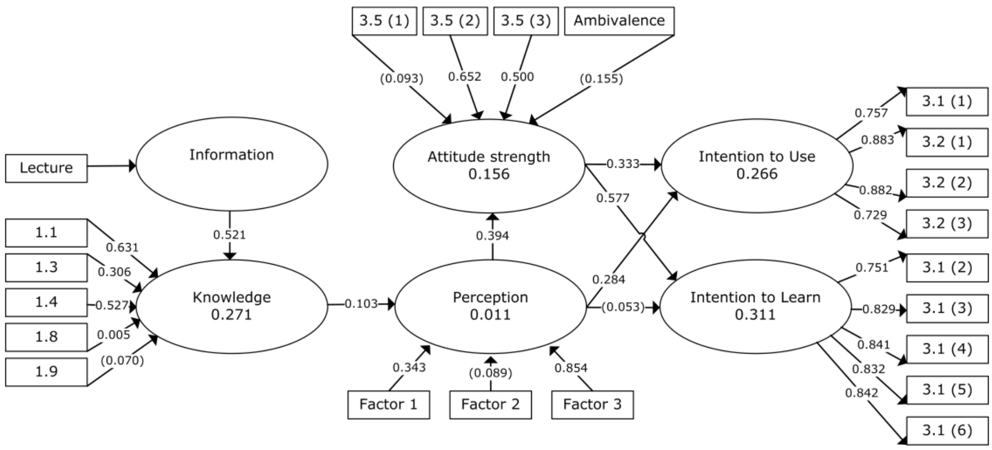


Figure 27. Structural equation modeling results

Evaluation of reflective measurement models (ITL and ITU)

Unidimensionality: For reflective variables it is tested whether unidimensionality is met. Sahmer, Hanafi, and El Qannari (2006) propose to use the latent root criterion which states that the first eigenvalue of the correlation matrix of items has to exceed one, and the second value has to be smaller than one. We use the two stage procedure described by Sahmer et al. (2006). The first stage consists of testing H_0: $\lambda_1 = 1$ and H_a: $\lambda_1 > 1$. According to Karlis, Saporta, and Spinakis (2003), H_a can be accepted if $\lambda_i > 1 + 2\sqrt{\frac{p-1}{n-1}}$ where p equals the number of manifest items and n indicates sample size. For the ITU and ITL constructs, the first eigenvalue should exceed 1.129 and 1.149 respectively. Since the eigenvalues for ITU and ITL are equal to 2.733 and 3.407, we accept H_a. The second stage in the assessment of unidimensionality centers around testing H_0: $\lambda_2 \geq 1$ and H_a: $\lambda_2 < 1$, for which the original Kaiser-Gutman criterium is applied. The second eigenvalue is smaller than 1 for both constructs. Therefore, it is concluded that both constructs can be considered unidimensional.

Indicator reliability: The indicator reliability specifies the part of an indicator's variance that can be explained by the underlying latent variable. At least 50% of an indicator's variance should be explained by the latent variable for reflective indicators (*i.e.* loading above 0.70). This also implies that the shared variance between a construct and its indicator is larger than the measurement error (Hair Jr, Hult, Ringle, & Sarstedt, 2013). For both the ITU and ITL construct all the loadings exceed the recommended 0.70 cut-off value.

Construct reliability: For the internal consistency reliability the composite reliability is used as the Cronbach's alpha is sensitive to the number of items in the scale and is more conservative. The composite reliability is acceptable for exploratory research when values of 0.60 or higher are obtained (Hair Jr et al., 2013). For both latent variables ITU and ITL the composite reliability values are above 0.85 which is satisfactory (Nunnally & Bernstein, 1994).

Convergent validity: For the convergent validity (*i.e.* the extent to which a measure correlates positively with alternative measures of the same construct (Hair Jr et al., 2013)) the outer loadings and average variance extracted (AVE) are used. The AVE is calculated as the sum of the squared loadings divided by the number of indicators. The outer loadings are all higher than 0.70 and the AVE above 0.5 and, therefore, acceptable. An AVE value of less than 0.50 is considered insufficient, as more variance is due to error variance than to indicator variance.

Discriminant validity: The discriminant validity is the extent to which a construct is distinct from other constructs, or in other words is unique. The cross loadings do not exceed the indicators' outer loadings indicating that also discriminant validity is met. Furthermore, the Fornell-Larcker criterion is also met (Fornell & Larcker, 1981). The criterion compares the square root of the AVE values with the latent variable correlations. An overview of the results of the Fornell-Larcker criterion is provided in Table 29. The table contains the latent variable correlations and the diagonal contains the square root of the AVE.

Table 29. Results Fornell-Larcker criterion

	Knowledge	**Perception**	**Attitude strength**	**Intention to Use**	**Intention to Learn**
Knowledge	Formative measurement model				
Perception	0.103	Formative measurement model			
Attitude strength	0.108	0.394	Formative measurement model		
Intention to Use	0.054	0.415	0.445	**0.816**	
Intention to Learn	0.065	0.175	0.556	0.434	**0.820**

An overview of the results of the overall reflective measurement models is provided in Table 30.

Table 30. Estimation results and psychometric properties of reflective measurement models

Latent variable	Indicators	Loadings	Indicator reliability	Composite reliability	AVE	Discriminant validity?
Intention to Use	3.1 (1)	0.757	0.573	0.888	0.666	Yes
	3.2 (1)	0.883	0.780			
	3.2 (2)	0.882	0.778			
	3.2 (3)	0.729	0.531			
Intention to Learn	3.1 (2)	0.751	0.564	0.911	0.672	Yes
	3.1 (3)	0.829	0.687			
	3.1 (4)	0.841	0.707			
	3.1 (5)	0.832	0.692			
	3.1 (6)	0.842	0.709			

Evaluation of formative measurement models (Knowledge, Perception, and Attitude strength)

When compared to reflective models, formative constructs demand a different evaluation of the measurement model as indicators are not correlated. As a result, the criteria used for reflective constructs cannot be directly transferred to formative constructs (Diamantopoulos, 1999).

Indicator reliability: Indicator reliability is examined by verifying whether high correlations exists between indicators. These high correlations are not expected in case of formative measurement models. In this model, *c*ollinearity does not reach critical levels. After checking the variance inflation factor (VIF) values we conclude that multicollinearity does not pose any problems. As a rule of thumb, it is suggested that the VIF should not exceed a value of 10 (Götz, Liehr-Gobbers, & Krafft, 2010).

Using a bootstrapping procedure it is evaluated which indicators are significant and relevant. The results of the bootstrapping procedure for the formative measurement models are provided in Table 31. The null hypothesis, stating that an outer weight equals zero (*i.e.* has no significant effect), is rejected when the interval does not include zero. From the table it can be concluded that three indicators are not significant and for that reason these are further investigated.

Two of the indicators (*i.e.* indicator '1.8' and 'Factor 2') are kept within the model. Indicator '1.9' is deleted from the model because its outer loading is not significant.

Construct reliability: It is suggested to use a general question, which might be considered reflective, related to each of the formative constructs in order to evaluate formative measurement model's external validity (Reinartz, Krafft, & Hoyer, 2004). However, no question is taken into account in our survey as the questionnaire is already perceived as being too long. As a consequence, the external validity of the formative constructs cannot be evaluated.

Convergent and discriminant validity: Formative indicators do not have to be strongly interrelated implying that the examination of convergent and discriminant validity, using criteria similar to those associated with reflective measurement models, are not meaningful in this context. Still, discriminant validity can be evaluated by testing whether the correlation between constructs are not perfect (*i.e.* equal to one). In this study it is concluded that discriminant validity applies for all formative constructs.

Table 31. Results bootstrapping procedure

Latent variable	**Indicator**	**Outer weights (Outer Loadings)**	**Significance level[a]**	**Confidence interval[b]**
Knowledge	1.1	0.631 (0.794)	***	[0.540;0.722]
	1.3	0.306 (0.445)	***	[0.204;0.408]
	1.4	0.527 (0.687)	***	[0.427;0.626]
	1.8	0.005 (0.207)	NS	[-0.104;0.114]
	1.9	-0.070 (0.002)	NS	[-0.173;0.033]
Perception	Factor 1	0.343 (0.591)	***	[0.194;0.492]
	Factor 2	-0.089 (0.145)	NS	[-0.222;0.044]
	Factor 3	0.854 (0.948)	***	[0.758;0.950]
Attitude strength	3.5 (1)	-0.093 (-0.038)	*	[-0.183;-0.003]
	3.5 (2)	0.652 (0.862)	***	[0.558;0.746]
	3.5 (3)	0.500 (0.759)	***	[0.398;0.602]
	Ambivalence	-0.155 (-0.354)	***	[-0.247;-0.063]

*a NS = Not significant; * = p < .10; ** = p < .05; *** = p < .01*

b Bootstrap confidence intervals for 10% probability of error

Evaluation of the structural model

Taking into account the results of the measurement model, the structural equation model is adapted and recalculated. The results are provided in Figure 28. The main focus of a structural model in PLS analysis is on the predictive power in terms of variance explained, as well as on the significance of all path estimates. To assess the hypotheses accompanying the various parameters, a bootstrapping procedure is used, the results of this procedure are shown in Figure 29. Next, the structural model is evaluated.

Predictive accuracy – R^2: the model's predictive accuracy is evaluated using the R^2 values of the endogenous constructs (*i.e.* ITU and ITL). It is difficult to define rules of thumb for acceptable R^2 values as they depend on the model complexity and the research discipline (Hair Jr et al., 2013). According to Chin (1998), R^2 values of 0.67, 0.33 and 0.19 can be considered as respectively strong, moderate and weak. Whereas this might be true for disciplines such as customer satisfaction or loyalty, in disciplines such as consumer behavior, which is more comparable to our study, R^2 values of 0.20 are considered high (Hair Jr et al., 2013). Therefore, it can be concluded that the R^2 values in our study are moderate, except for the R^2 value of 'Perception' which is weak. To test for the R^2's significance, a bootstrap confidence interval for R^2 is calculated by using the equation described in Tenenhaus, Vinzi, Chatelin, and Lauro (2005). The R^2 95% bootstrap confidence intervals for ITU and ITL amount to respectively [0.201,0.333] and [0.247,0.379].

Relationships latent variables: The relationships between the latent variables are analyzed using the path coefficients and a bootstrapping procedure. The path coefficients all indicate positive relationships, except the relationship from 'Perception' to ITL. However, the relationships are not very strong. Nevertheless, based on the bootstrapping procedure it can be concluded that all relationships are significant with a significance level of 1%, except for '1.8' under 'Knowledge', 'Factor 2' under 'Perception' and the relationship between 'Perception' and ITL.

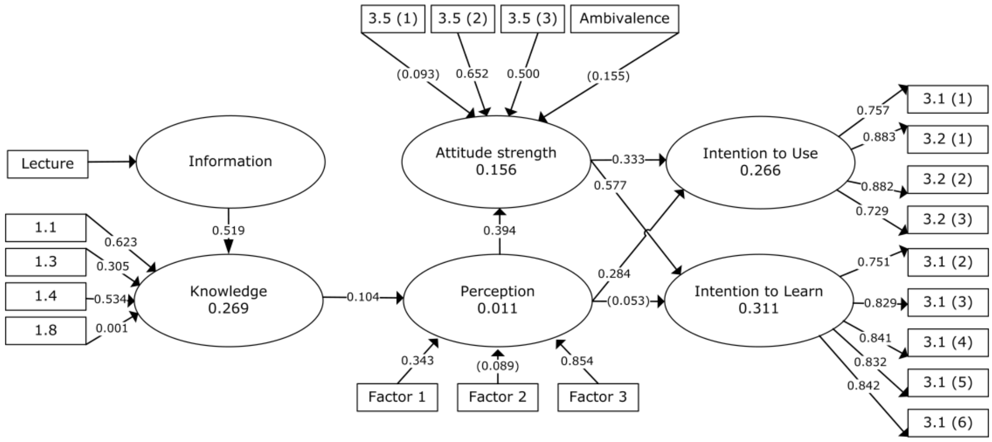


Figure 28. Final structural equation modeling results

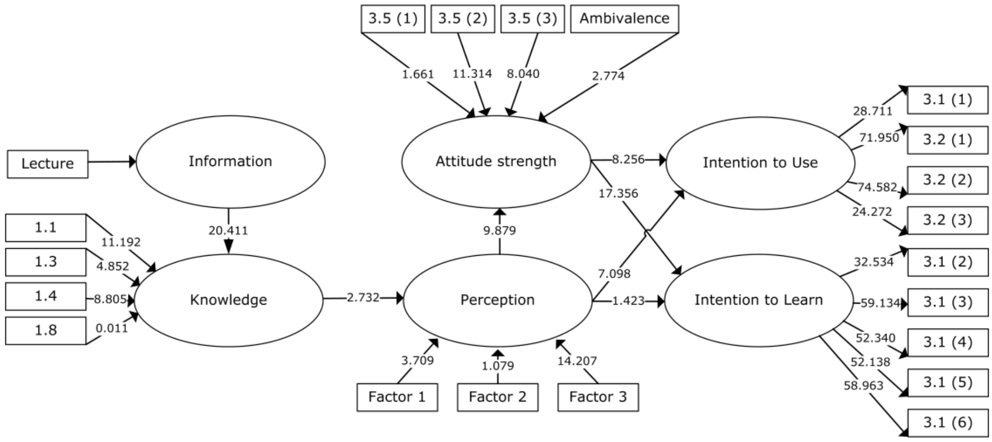


Figure 29. Final structural equation modeling bootstrapping results

Predictive relevance path model: In the following step a blindfolding procedure is run in SmartPLS to have an idea of the predictive relevance of the path model. From this procedure the Stone-Geisser's Q^2 value is obtained (Geisser, 1974). For the latent variable ITU the Q^2 value amounts to 0.173 which means the model has a medium predictive relevance for ITU. Also for the latent variable ITL the Q^2 value is medium and amounts to 0.207.

Effect size: The impact of omitting an exogenous construct on the R^2 value of all endogenous constructs can be evaluated. As such, the contribution of each exogenous construct in terms of explanatory power can be compared. The measurement is referred to as the f^2 effect size. Values for f^2 of 0.02, 0.15 and 0.35 indicate the latent exogenous variable's weak, moderate or substantial influence on the latent endogenous variable (Cohen, 2013). The exclusion of 'Attitude strength' would result in a significant drop in the variance explained for ITL as the f^2 amounts to 0.406. The effect of 'Attitude strength' on ITU is weak (f^2 = 0.119). 'Knowledge' has a weak effect on the R^2 value of all endogenous variables. 'Perception' has only a weak effect on ITU and ITL with f^2 values of respectively 0.235, 0.105 and -0.028.

Mediation effect: A mediation effect exists when a third variable intervenes between two other related constructs, as in our example 'Attitude strength' mediates the constructs 'Perception' and ITU (*i.e.* H5) and 'Perception' and ITL (*i.e.* H6). In order to test for mediating effects, we follow the bootstrap procedure prescribed by Preacher and Hayes (2008). We first check whether the direct effect from 'Perception' to ITU and ITL is significant. Both direct effects are significant. Therefore, we include the mediator 'Attitude strength' to check whether it absorbs some or the entire effect. The indirect effects are all significant with a t-value of 5.7 and 8.4 for respectively ITU and ITL, implying that the mediator absorbs at least some of the direct effect. In order to evaluate how much 'Attitude strength' absorbs, the variance accounted for (VAF) is calculated. The VAF is respectively 51% and -13% for ITU and ITL. Based on these results it can be concluded that 'Attitude strength' is having a partial mediation effect in case of ITU. In case of ITL a suppressor effect is found as the inclusion of the mediator 'Attitude strength' changes the sign of the direct relationship between 'Perception' and ITL. An overview of the intermediate results is provided in Table 32.

Table 32. Results mediation effect

	Path coefficient	Bootstrap t-value
Direct effect		
Perception → ITU	0.423	12.15
Perception → ITL	0.175	4.35
Indirect effect		
Perception → Attitude strength	0.394	9.88
Attitude strength → ITU	0.333	8.26
Perception → ITU	0.284	7.10
		0.394*0.333=0.131
Perception → Attitude strength	0.394	9.88
Attitude strength → ITL	0.577	17.36
Perception → ITL	-0.053	1.42
		0.394*0.577=0.227
Total effect		
ITU = 0.423 + 0.131 = 0.554		
ITL = 0.175 + 0.227 = 0.402		

From the analysis, it is found that 'Information' has a significant positive effect on 'Knowledge', *i.e.* H1 is supported. Also, 'Knowledge' has a significant positive influence on the perception concerning biomass, *i.e.* H2 is confirmed. Furthermore, 'Perception' is found to have a mediation effect on the relationship between 'Knowledge' and 'Attitude strength'. A negative relationship is found between 'Perception' and ITL implying that H3 is not supported as a positive relationship was assumed, however, this relationship is not significant. Furthermore, when only the direct effect is taken into account, a positive relationship is found. The found suppressor effect can be due to the fact that when respondents had a positive perception and a strong attitude, their willingness to learn more about bioenergy was low because their attitude was already formed. A significant positive relation was found between 'Perception' and ITU, supporting H4. Both H5 and H6 can be confirmed as it can be concluded that 'Attitude strength' is a mediator between 'Perception' and ITU and ITL. Finally, the predictive value of the structural model is concluded to be moderate.

Evaluation heterogeneity

It is useful to see whether the relationships in the path model differ significantly based on gender. Becker, Klein, and Wetzels (2012) even warn that the failure to consider heterogeneity can be a threat to the validity of PLS-SEM results as incorrect conclusions can be drawn. A multigroup analysis (MGA) is used to check for differences between coefficients. We will use the non-parametric approach prescribed by Henseler (2012) in order to perform this analysis. The results of the analysis are shown in Table 33, when the PLS-MGA p-value is smaller than 0.05 or higher than 0.95, a significant difference is found between groups.

Table 33. Results MGA gender

Relationship	**PLS-MGA p-value**
Attitude strength → ITL	0.14
Attitude strength → ITU	0.02
Perception → ITL	0.98
Perception → ITU	0.99
Perception → Attitude strength	0.12
Knowledge → Perception	0.67
Information → Knowledge	0.63

Based on gender we find significant differences in the relationship between ‘Perception’ and both ITL and ITU. Females have a larger positive relationship between ‘Perception’ and ITU in comparison with male respondents. Whereas, the relationship ‘Perception-ITL’ is not significant in case of female respondents. Furthermore, it is concluded that the relationship between ‘Attitude strength’ and ITU is significantly more positive for male than female respondents.

5.4. Discussion and conclusion

Bioenergy is one of the main sources of renewable energy that is also important in order to attain the EU 20-20-20 targets. However, many bioenergy projects fail due to a lack of public acceptance. Taking into account that the opinion of young people is relevant for future policy makers and that children and young citizens influence long-term behavioral changes in the use of renewable energy sources, this study is focused on young citizens. The goal of the study is to identify the knowledge, perception, attitude strength and behavioral intentions of young people towards biomass for energy purposes. From the study it can be concluded that the general level of knowledge about bioenergy is rather low. This knowledge level can, at least in the short term, be improved by providing a lecture. In general, perceptions and attitudes of pupils and students towards bioenergy are positive. Based on factor analysis the attitude towards bioenergy can be divided into two dimensions: (1) intention to learn and (2) intention to use. From the analysis it seems that the respondents were positive towards the usage of biomass for their energy provision, however, they were less likely to learn more about it. Despite the positive intention to use bioenergy, respondents did differentiate their perceptions based on the type of biomass. It seemed that the respondents were more positive towards the usage of waste streams as input source for bioenergy in comparison to wood. This can be explained by the local situation in Belgium. Finally, significant differences were found based on gender. Females appear to be more optimistic about the future role of bioenergy, are more positive towards the future use of bioenergy for their energy provision, but they are less willing to learn more about the topic. Although respondents indicated a rather negative intention to learn about the topic, more attention towards sustainable issues such as renewable energy should be provided in schools in order to be more critical about the role of these kinds of alternative energy sources in our future energy provision.

In order to make a decision concerning long-term effects of lectures, a follow-up study is necessary. Although respondents indicated a negative intention to learn about the topic, we still advise to restructure the current curricula and pay more attention towards sustainable issues such as renewable energy. The fact that the intention to learn is low, about topics which are of high importance for the future sustainability of the society, might even be alarming. Apparently, young people are in general not so much concerned with this issue. Using alternative, more interactive (*i.e.* student-centered) teaching methods, intentions to learn might rise. It would be interesting to add some direct experiences (e.g. a site visit) for the students in order to increase chances of having a significant effect on behavior. Also, the transferred knowledge might be more long lasting depending on the teaching method (Çelikler, 2013). Further research has to indicate which teaching method is most suitable for these topics. The method that was used here (*i.e.* 30 minute powerpoint lecture) at least suggested a general fatigue concerning the topic of sustainability. Restructuring the current curricula with more attention to potential solutions might help in rejuvenating the interest of young people concerning sustainability. Besides, more attention should be paid to the content of lectures concerning sustainability in order to avoid repetition and provide a broader background to the topic. Kandpal and Broman (2014) provided some suggestions for curriculum development for renewable energy education based on a global review. In our study we did not investigate teachers' current level of knowledge. However, before re-structuring curricula, it is necessary that teachers have a sufficient background on the topic. As Çelikler (2013) noted, it is critical to educate pre-service teachers as they will inform future generations of school children about renewable energy and resources.

From the structural equation modeling it can be concluded that an increased knowledge level has a positive impact on the perception, attitude strength and in the end the intention to use. A negative relationship is found between perception and intention to learn. However, the predictive value of the model is rather small. Furthermore, the questions chosen, based on previous research, to measure intention to learn might not be the preferred ones. Discussing with teachers, parents or friends about bioenergy might not be popular among young people. Results might change when asking for their interesting in watching for example documentaries concerning the topic. In order to have a better grasp of the impact of providing information or knowledge on the perception and attitudes of respondents, a further in-depth study is needed. This is important to better understand the relationship between the provision of more information and the public acceptance of bioenergy projects. Yohanis (2012) already concluded that a single approach to changing behavior, such as the provision of information, will not be sufficient to induce meaningful levels of behavioral change. However, independent of the effective influence of providing more information on the acceptance of bioenergy projects, students should gain more information concerning renewable energy in order to be more critical about the role of these kinds of alternative energy sources in our future energy provision.

Chapter 6.

Conclusions

6.1. Primary objectives

In this dissertation it was investigated what the potential is of biomass residue streams to be valorized as a source of renewable energy and materials. Biomass is one of the most abundant and versatile sources for renewable energy. Therefore, it is one of the main sources to attain the 20-20-20 EU targets. In Western European countries, the focus currently lies on clean and pure biomass like wood pellets and energy maize. Moreover, these are often imported over large distances or compete with food and feed. Furthermore, the existing energy conversion plants are mostly dedicated to one biomass input source and rely on the most appropriate conversion technology for that type of biomass. Also, in many cases they produce one specific output like biofuels or electricity and/or heat. Even more important in the discussion concerning biomass is the recent trend towards a biobased economy in which it is recognized that biomass can preferably be used following a cascading principle. First biomass should produce high value materials such as chemicals and only in a last phase to produce energy. Additionally, several biomass resources are regionally available in large amounts and do not compete with food or feed, therefore, these streams might have a large potential to be used as a source of renewable energy and materials. To facilitate the efficient use of these regionally available biomass residue streams and to help stimulate a transition towards a biobased economy, the Energy Conversion Park (ECP) concept which can be seen as a regional form of a biorefinery, is developed. An ECP is defined as a synergetic multidimensional biomass conversion site with a highly integrated set of conversion technologies in which a multitude of regionally available biomass (residue) sources are converted into energy and materials.

In order to answer to the main research question whether biomass residue streams have potential to be valorized as a source of renewable energy and materials, a general development process is established (Chapter 1). Different aspects of the ECP concept have to be taken into account in order to provide a clear answer. A location has to be selected, the concept has to be technically feasible, economically viable and environmentally friendly and the concept has to be accepted by the broader public before it can be implemented. Therefore, this dissertation provides an answer to the different questions raised and formulates an integrated answer based on the various results. In the second chapter a methodology is developed to search for the potential most interesting location for an ECP. Next to a location, also the techno-economic feasibility of the ECP is investigated in order to determine the most interesting concept from an economic point of view (Chapter 3). However, in case of renewable energy it is important that the output products can be taken into account for the EU targets and, therefore, an environmental assessment is performed following the guidelines prescribed by the renewable energy directive (RED) (Chapter 4). Finally, the social knowledge and perception will influence the acceptance of an ECP (Chapter 5).

When developing an energy conversion park one of the first hurdles to take is to determine a potential interesting location as it is based on regionally available biomass sources. A detailed analysis of all potential locations would take a lot of time and cost many resources, therefore, a macro screening approach is proposed in Chapter 2. The approach exists of five steps. Firstly, all criteria on which an alternative can be rated, must be identified. Then, data must be gathered for each criterion agreed upon to be included in the analysis. These data provide a score for each alternative. In a third step a weight is assigned to each criterion considering not every criterion is equally important. Fourthly, final scores are found for every alternative by summing the multiplications of the scores and the weights per criterion. Finally, a spatial representation of the weighted criteria can be obtained by combining the MCDA method with GIS. The macro screening only gives an indication of the potentially interesting locations and cannot select the best location among the alternatives. However, the case study has shown that it was possible to drastically reduce the potential locations to the most interesting ones. It can therefore be concluded that the macro screening method provides a fast and efficient way to explore the market for site selection. Moreover, it is a supportive and motivational tool to utilize as input for the micro screening (*i.e.* detailed location analysis) to support and motivate partners, investors, and policy makers and that allows for studying the possibilities of building a plant at a specific location.

After the potential interesting locations are determined, the available regional biomass residue types are inventoried and the most important stakeholders such as suppliers of biomass, investors, government, and heat customers are consulted. This stakeholder participation contributes to the likelihood of acceptance and eventual realization of the concepts. Each proposed design has to be evaluated: technically, economically as well as environmentally. An interesting evaluation methodology to perform the three analyses is an extended techno-economic assessment. In Chapter 3 the techno-economic assessment (TEA) methodology is introduced. This methodology has become more popular since 2010, however, an existing framework or general guidelines were still missing. In this dissertation we filled this gap. A TEA can be divided into four different phases which are performed in an iterative way as information gathering is expensive. First, a market study is performed. Second, a preliminary process design is defined and translated into a simplified process flow diagram and mass and energy balance. Third, this information is directly integrated into a dynamic economic evaluation. From this analysis the profitability is identified. Fourth, a risk analysis is performed in order to identify the potential barriers. Based on the results of this cycle, risk reduction strategies can be formulated and steps can be repeated when the results sound promising. A TEA can help to optimize the development of a process and to determine the most important parameters. Consistently applying the methodology will enhance chances of success when introducing (innovative) processes on the market. For that reason, the development process will be divided in different steps or stages after which a go/no-go decision has to be taken. Optionally, an environmental analysis can be added as a fifth phase in order to get an extended TEA (see Chapter 4). The TEA methodology is applied on two case studies from which it is concluded that bioenergy projects can be economically feasible under optimal circumstances, however, from the sensitivity analysis it seemed that risks are high. By simultaneously producing high value materials from biomass, the economic feasibility can be increased.

In Chapter 4 the TEA methodology introduced in chapter 3 is extended with the environmental analysis. Only when the products produced within the biorefinery are sustainable, it is interesting for the society. It is even more interesting if the products can be taken into account for attaining the 20-20-20 EU targets. Therefore, it is verified whether the products produced in a case study can be taken into account for these targets and at the same time an evaluation is made of the calculation guidelines as prescribed in the RED using the B-SAT tool. Furthermore, the calculations are compared with calculations based on exergy. This is done because the RED guidelines are not made with complex processes producing materials and energy in mind. From the analysis it is concluded that depending on the specific interpretation of the guidelines, output products might not be taken into account for the EU targets. Furthermore, it is concluded that the guidelines provided by the RED are based on practical decisions rather than objective sustainability criteria. With the guidelines in their current form, it can be advised to combine sustainability assessments based on the RED guidelines with other more holistic assessments in order to obtain a more precise view on the sustainability of the project. The guidelines still need to be brought in accordance with the concept of resource efficiency which is implemented by the European Union and which is followed by the 2012 Commission's strategy and action plan 'Innovating for Sustainable Growth: a Bio-economy for Europe' in which focus is put on materials, rather than energy.

Even if an optimal location is chosen and the sustainability of an ECP is proven, projects may still be hindered due to social barriers. Taking into account that (1) young citizen's knowledge and perceptions of bioenergy are important for future policy makers and (2) that experience has shown that they are instrumental in achieving long-term behavioral changes in the use of renewable energy sources, in Chapter 5 the knowledge, perception and attitude of young people towards biomass for energy purposes is investigated. It is concluded that the knowledge of young people concerning renewable energy is very low and that this level can be raised by providing information. Furthermore, positive relationships are found between knowledge, perception, attitude strength and intention use. Therefore, it is advised to increase the knowledge level of young people concerning sustainability in general and renewable energy sources specifically.

6.2. General conclusions

Combining the answers provided by reaching the primary objectives, the question whether biomass residue streams have potential to be valorized as a source of renewable energy and materials can be responded. In Chapter 2, a macro screening methodology was developed to determine the potential most interesting location for an energy conversion park. The information from this perspective has led us to conclude that it is viable for an investor to efficiently search for a location in a more substantiated way. Using this methodology investors can better convince for example policy makers of the potential of the chosen location for the project. However, a macro screening cannot stand alone as a decision tool and has to be followed by a thorough micro screening of the best-scoring locations. In the next chapter it was revealed that a techno-economic assessment is very useful when evaluating innovative biomass projects. By integrating technical and economic calculations, more insight can be gained into the parameters that have the highest influence on the economic feasibility. Moreover, it can be concluded that biomass projects focusing solely on energy are in many cases barely economically feasible. Therefore, investors have to search for energy conversion park concepts in which the production of energy is combined with the production of high value materials. From the third chapter, it is concluded that the techno-economic analysis can be extended with an environmental analysis in order to check whether the output of the ECP follows the prescriptions of the RED. However, it is proven that the RED is not developed with complex biomass processes in mind that produce both energy and materials. Therefore, an alternative methodology, *i.e.* exergy analysis, is proposed. Also, it was clear that the end-of-waste criteria leave room for interpretation, resulting in conflicting decisions based on the current guidelines. From the fifth chapter, it is noticed that the general knowledge level of young people concerning renewable energy is very low. This level of knowledge can be increased by providing information. However, the methodology used to transfer knowledge has to be carefully selected and should preferably be student-centered. Furthermore, it can be concluded that a positive relationship exists between the perception concerning bioenergy, the attitude strength and intention to use.

Therefore, it is generally concluded that biomass is indeed a versatile source of renewable energy. Taken into account that biomass can be used for high value materials and that this will have a positive effect on the economic feasibility, it is highly recommended to focus on biomass energy conversion concepts in which both are combined. Furthermore, it is highly recommended to investors and policy makers to use the extended techno-economic assessment methodology as a standard decision support tool and to adopt it from the preliminary idea until the implementation phase in order to have a detailed insight in the risks involved with the new project. Moreover, it is recommended to reevaluate the current curricula in order to (1) raise the knowledge of young people concerning renewable energy, as well as (2) improve the structure of the current content concerning sustainability. This should result in reducing the fatigue towards the topic and have a positive effect on the intentions to learn and use it.

At this moment, biomass energy conversion concepts are not yet built in practice as risks are still high, economic investments are large, social acceptance is low, and policy support is unsure. However, single technologies converting biomass to energy or materials already exists and are interesting cases to extend to complete energy conversion concepts, as can be concluded from the case studies. Main challenges can be found in: (1) finding new business models to implement these concepts with multiple stakeholders involved, (2) informing the broader public in a way that leads to an increase in social acceptance, and (3) implementing the extended techno-economic evaluation methodology as a standard methodology that is used by investors as well as policy makers.

6.3. Discussion and suggestions for further research

This section provides a discussion about the use of and suggestions for further research in the field of the extended techno-economic assessments and the increase of public acceptance.

Taking into account that (1) the main focus of the guidelines prescribed in the RED are directed towards energy, (2) that major technical, strategic and commercial challenges exist for biomass projects, and (3) that the proposed extended techno-economic assessment methodology can help to answer many of the concerns, the methodology needs to be further refined.

In Chapter 4 it is shown that the current guidelines laid down in the RED are not made with biorefinery concepts in mind. Furthermore, it is shown that some decisions, e.g. the label of waste, are open for discussion. Therefore, an appropriate environmental assessment methodology has to be searched for. Exergy seems to be an interesting methodology in the framework of biobased processes, however, some disadvantages exists. Due to technical and theoretical limitations, the integration of exergy-based impact measures is not straightforward. Another disadvantage of the use of exergy is that exergy aggregates the different forms of energy and materials and the difference between for example renewable and non-renewable energy is hard to make (Maes and Van Passel, 2014). Moreover, the results seem to be difficult to interpret and, therefore, not often used for sustainability assessments (Buytaert et al., 2011). A sustainability assessment tool which gives a broader view on the sustainability of an entire process is LCA (Garofalo, 2010). Although LCA is a popular tool, it has a number of limitations. (i) It is dependent on the quality and availability of accurate data which does not always exist or can be expensive to obtain. (ii) Numerous assumptions have to be made implying it is inherently subjective. (iii) Sustainability assessment approaches based on LCA, result in disparate indicators which makes generalization hard as aggregation is not convenient and the approaches are often context-specific (Maes and Van Passel, 2014). The excess of sustainability assessment tools highlights the need of a systematic approach to give a well-structured methodology which is easy to reproduce and which includes all important aspects (R. K. Singh, Murty, Gupta, & Dikshit, 2009). Therefore, the different existing tools need to be evaluated in order to select or develop an optimal approach for the evaluation of ECP concepts.

Different ECP concepts can be compared using an extended techno-economic assessment. In Chapter 3 it is already noticed that a step-by-step integration of the different biomass sources and processing technologies is more likely in practice. The specific conditions and prices under which these kinds of decisions, *i.e.* investments under uncertainty, which are sometimes irreversible and/or can be delayed, will be taken, can be analyzed using the theory of real options which is based on dynamic programming (Dixit and Pindyck, 1994). Furthermore, the choice for the preferred pathway should not only be made based on cost minimizing principles, however, should also look at the most efficient pathways. The Data Envelopment Analysis (DEA) technique is a widely used tool to measure productivity and efficiency and is, therefore, an interesting methodology to apply on biobased cases (Grigoroudis, Petridis, & Arabatzis, 2014). Furthermore, the efficiency assessment can include the definition of a benchmark technology. This will be done by the construction of a production function of a completely efficient economic entity in either a deterministic way or a stochastic way (Reinhard, Knox Lovell, & Thijssen, 2000). An efficiency assessment will enable firms to identify technologies as benchmark technologies or inefficient processes. If a process is not profitable and considered inefficient towards a benchmark, research could be directed to overcome the shortcomings of the technology. On the other hand, if a technology that is not profitable is considered to be efficient and seen as a benchmark technology, the problem may be inherent to the general technology or business case used. In this case new pathways can render a solution. Moreover, this efficiency assessment can be implemented in both an economic and ecological way by including environmental aspects such as resource use, waste production, and water use. This way it provides a link between the techno-economic assessment and the sustainability assessment.

Also, we did not yet provide a discussion of the optimal capacity of an ECP concept. Since we try to use non-linear models that take into account economies of scale as much as possible, it is promising to also determine the optimal scale of the different installations. Some installations, such as digesters, benefit from economies of scale. However, simultaneously they are limited in size because of physical limitations (*i.e.* size of the screw). Furthermore, larger scales also imply more biomass that has to be transported to the plant. With increasing distances transport costs can become substantial and can even diminish the potential gain created by economies of scale. Therefore, it is advised to consider non-linear optimization to determine the optimal size of ECP concepts and to conduct a sensitivity analysis on this optimization.

There is not only additional research needed in the field of the extended techno-economic assessment, but also the research concerning perception of biomass and the influence of an increased knowledge level deserves further attention. In this dissertation it was investigated how the provision of a lecture influence the knowledge level of respondents and whether an effect could be found on perception and intention to use biomass and learn more about it. However, it was concluded that the classic teaching method (*i.e.* presenting a power point presentation) was not the best option. The knowledge level did increase at least on the short term, however, within the time span of the dissertation a long term effect could not be tested. Furthermore, it was noticed that respondents didn't want to learn more about biomass. Therefore, further research has to look for other methods to increase the general knowledge level that have long term effects and that are appreciated by the respondents. Also, it was stated in the introduction of the dissertation that mass media plays an important role in shaping the public opinion. For that reason it also has to be investigated what the exact relationship is between an increased knowledge level and the impact of mass media. It was assumed in this research that people having more background information are more critical when interpreting messages send by mass media. This assumption is based on the statement that mass media influences public attitudes and perceptions most concerning topics that the public does not have regular or meaningful contact with. However, this hypothesis was not tested within the study.

Finally, further research taking into account the perceptions of policy makers and industry would be of major value. Next to the broader public, both these stakeholder categories are very important. A similar approach as for the students might be used. The most important difficulty will be the number of respondents. Especially for policy makers the number of potential respondents is limited if the case study is focused on Flanders (*i.e.* Northern part of Belgium). Bootstrapping procedures or permutation methods can be used to overcome this problem. Furthermore, the use of PLS SEM has the advantage that the number of respondents can be limited. Another difficulty might be the way in which the impact of more information is measured. We provided a lecture to the students to check the influence of more information on the perception of biomass. This lecture has to be changed in order to fit the background knowledge and interests of the other stakeholder categories. Alternatively a different approach, e.g. provision of information in the questionnaire itself, might be chosen. In general, stakeholders from policy and industry do not have a lot of time and it will be easier to gather the information using online-questionnaires which the respondents can fill out when it fits their agenda. Furthermore, it is worth mentioning that chances are high that the perceptions of stakeholder categories such as policy makers will have a major influence on the perception of the broader public and industry. When government believes in biobased concepts and provides support for these systems, communication in mass media should represent this positive viewpoint. This positive communication should be reflected in a general acceptance of ECP concepts and a stable investment climate. However, when policy makers do not believe in the concepts or regularly change the policy framework, the broader public will be skeptical and investors will wait for a clearer support system.

REFERENCES

Abdi, H. (2007). Kendall Rank Correlation. *Encyclopedia of Measurement and Statistics*. SAGE Publications, Inc. Thousand Oaks, CA, SAGE Publications, Inc.

Abubaker, J., Risberg, K., & Pell, M. (2012). Biogas residues as fertilisers – Effects on wheat growth and soil microbial activities. *Applied Energy, 99*(0), 126-134. doi: 10.1016/j.apenergy.2012.04.050.

Afionis, S., & Stringer, L. C. (2012). European Union leadership in biofuels regulation: Europe as a normative power? *Journal of Cleaner Production, 32*(0), 114-123. doi: 10.1016/j.jclepro.2012.03.034.

AgentschapNL. (2012). Verwachte voorlopige correctiebedragen voor warmte en warmtekracht in de SDE 2012. From http://www.agentschapnl.nl/actueel/nieuws/verwachte-voorlopige-correctiebedragen-voor-warmte-en-warmtekracht-de-sde-2012.

Ajzen, I. (1991). The theory of planned behavior. *Organizational behavior and human decision processes 50*(2): 179-211.

Ajzen, I. and M. Fishbein (1980). Understanding attitudes and predicting social. *Behaviour. Englewood Cliffs, NJ: Prentice-Hall.*

Al Seadi, T. (2004). Biogas from AD: BIOEXCELL Training Manual. *Project Deliverable of the BIOEXCELL project*. Biogas Centre of Excellence.

Ali, G., Nitivattananon, V., Abbas, S., & Sabir, M. (2012). Green waste to biogas: Renewable energy possibilities for Thailand's green markets. *Renewable and Sustainable Energy Reviews, 16*(7), 5423-5429. doi: 10.1016/j.rser.2012.05.021.

Allen, J., Browne, M., Hunter, A., Boyd, J., & Palmer, H. (1998). Logistics management and costs of biomass fuel supply. *International Journal of Physical Distribution & Logistics Management, 28* (6), 463-477.

Ananda, J. and G. Herath (2009). A critical review of multicriteria decision making methods with special reference to forest management and planning. *Ecological Economics 68*(10): 2535-2548. doi: 10.1016/j.ecolecon.2009.05.010.

Apostolakou, A. A., Kookos, I. K., Marazioti, C., & Angelopoulos, K. C. (2009). Techno-economic analysis of a biodiesel production process from vegetable oils. *Fuel Processing Technology, 90*(7–8), 1023-1031. doi: 10.1016/j.fuproc.2009.04.017.

Asveld, L., Est, R. v., & Stemerding, D. (2010). From biobased 0.0 to biobased 3.0: some propositions (T. Assessment, Trans.) (pp. 18). Den Haag.

Aydiner, C., Sen, U., Topcu, S., Ekinci, D., Altinay, A. D., Koseoglu-Imer, D. Y., & Keskinler, B. (2014). Techno-economic viability of innovative membrane systems in water and mass recovery from dairy wastewater. *Journal of Membrane Science, 458*(0), 66-75. doi: 10.1016/j.memsci.2014.01.058.

Ayoub, N., Martins, R., Wang, K., Seki, H., & Naka, Y. (2007). Two levels decision system for efficient planning and implementation of bioenergy production. *Energy Conversion and Management, 48*(3), 709-723. doi: 10.1016/j.enconman.2006.09.012.

Azuara, M., Kersten, S. R. A., & Kootstra, A. M. J. (2013). Recycling phosphorus by fast pyrolysis of pig manure: Concentration and extraction of phosphorus combined with formation of value-added pyrolysis products. *Biomass and Bioenergy, 49*(0), 171-180. doi: 10.1016/j.biombioe.2012.12.010.

Badera, J. and P. Kocoń (2014). Local community opinions regarding the socio-environmental aspects of lignite surface mining: Experiences from central Poland. *Energy Policy 66*(0): 507-516. doi: 10.1016/j.enpol.2013.11.048.

Baird, D. E., & Fisher, M. (2005). Neomillennial user experience design strategies: Utilizing social networking media to support "always on" learning styles. *Journal of educational technology systems, 34*(1), 5-32.

Balana, B. B., Mathijs, E., & Muys, B. (2010). Assessing the sustainability of forest management: An application of multicriteria decision analysis to community forests in northern Ethiopia. *Journal of Environmental Management, 91*(6), 1294-1304. doi: 10.1016/j.jenvman.2010.02.005.

Barber, N., Taylor, C., & Strick, S. (2009). Wine consumers' environmental knowledge and attitudes: influence on willingness to purchase. *International Journal of Wine Research, 1*(1), 59-72.

Barbiroli, G. (1997). The dynamics of technology : a methodological framework for techno-economic analyses. Dordrecht ; London, Kluwer Academic.

Barral, M. T., Paradelo, R., Moldes, A. B., Domínguez, M., & Díaz-Fierros, F. (2009). Utilization of MSW compost for organic matter conservation in agricultural soils of NW Spain. *Resources, Conservation and Recycling, 53*(9), 529-534. doi: 10.1016/j.resconrec.2009.04.001.

Beavers, A. S., Lounsbury, J. W., Richards, J. K., Huck, S. W., Skolits, G. J., & Esquivel, S. L. (2013). Practical considerations for using exploratory factor analysis in educational research. *Practical Assessment, Research & Evaluation, 18*(6), 2.

Becker, J.-M., Klein, K., & Wetzels, M. (2012). Hierarchical latent variable models in PLS-SEM: guidelines for using reflective-formative type models. *Long Range Planning, 45*(5), 359-394.

Belastingdienst (2012). Tarieven voor de vennootschapsbelasting in 2012. Retrieved June 11, 2012, from http://www.belastingdienst.nl/wps/wcm/connect/bldcontentnl/belastingdienst/zakelijk/winst/vennootschapsbelasting/veranderingen_vpb_2012/tarieven_vpb_2012.

Belgian Federal Government (Brussels) (2008). Labour costs for the industry (NACE B-F) per hour. From http://statbel.fgov.be/nl/statistieken/cijfers/arbeid_leven/lonen/activiteit/index.jsp.

Bell, M. L., Hobbs, B. F., Elliott, E. M., Ellis, H., & Robinson, Z. (2000). An Evaluation of Multicriteria Decision-Making Methods in Integrated Assessment of Climate Policy. Research and Practice in Multiple Criteria Decision Making. In Y. Y. Haimes & R. E. Steuer (Eds.), (Vol. 487, pp. 228-237): Springer Berlin Heidelberg.

Bernheim, B. D., & Whinston, M. D. (2008). *Microeconomics*. New York: McGraw-Hill/Irwin.

Biezma, M. V., & Cristóbal, J. R. S. (2006). Investment criteria for the selection of cogeneration plants - a state of the art review. *Applied Thermal Engineering, 26*(5-6), 583-588. doi: 10.1016/j.applthermaleng.2005.07.006.

Boggia, A., & Cortina, C. (2010). Measuring sustainable development using a multicriteria model: A case study. *Journal of Environmental Management, 91*(11), 2301-2306. doi: 10.1016/j.jenvman.2010.06.009.

Börjesson, P., & Tufvesson, L. M. (2011). Agricultural crop-based biofuels–resource efficiency and environmental performance including direct land use changes. *Journal of Cleaner Production, 19*(2), 108-120.

Bougnom, B. P., Niederkofler, C., Knapp, B. A., Stimpfl, E., & Insam, H. (2012). Residues from renewable energy production: Their value for fertilizing pastures. *Biomass and Bioenergy, 39*(0), 290-295. doi: 10.1016/j.biombioe.2012.01.017.

Boukis, I., Vassilakos, N., Kontopoulos, G., & Karellas, S. (2009). Policy plan for the use of biomass and biofuels in Greece: Part I: Available biomass and methodology. *Renewable and Sustainable Energy Reviews, 13*(5), 971-985. doi: 10.1016/j.rser.2008.02.007.

Bozell, J. J. (2008). Feedstocks for the future–biorefinery production of chemicals from renewable carbon. *CLEAN–Soil, Air, Water, 36*(8), 641-647.

BPF (2013). Samenstelling huidige maximumprijzen. Retrieved May 7, 2013, from http://www.petrolfed.be/nl/maximumprijzen/samenstelling-huidige-maximumprijzen.

Braekevelt, A. and K. Schelfhout (2013). Inventaris Biomassa 2011-2012. From http://www.ovam.be/sites/default/files/Inventaris%20Biomassa%202011-2012_0.pdf.

Bram, S., De Ruyck, J., & Lavric, D. (2009). Using biomass: A system perturbation analysis. *Applied Energy, 86*(2), 194-201. doi: 10.1016/j.apenergy.2007.12.002.

Bridgwater, A. V., Toft, A. J., & Brammer, J. G. (2002). A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. *Renewable and Sustainable Energy Reviews, 6*(3), 181-246. doi: 10.1016/S1364-0321(01)00010-7.

Briedis, J. I., Wilson, J. S., Benjamin, Jeffrey G., & Wagner, R. G. (2011). Biomass retention following whole-tree, energy wood harvests in central Maine: Adherence to five state guidelines. *Biomass and Bioenergy, 35*(8), 3552-3560. doi: 10.1016/j.biombioe.2011.05.018.

Brown, T. R., Wright, M. M., & Brown, R. C. (2011). Estimating profitability of two biochar production scenarios: slow pyrolysis vs fast pyrolysis. *Biofuels, Bioproducts and Biorefining, 5*(1), 54-68. doi: 10.1002/bbb.254.

Buchholz, T., Rametsteiner, E., Volk, T. A., & Luzadis, V. A. (2009). Multi Criteria Analysis for bioenergy systems assessments. *Energy Policy, 37*(2), 484-495. doi: 10.1016/j.enpol.2008.09.054.

Buchholz, T. S., Volk, T. A., & Luzadis, V. A. (2007). A participatory systems approach to modeling social, economic, and ecological components of bioenergy. *Energy Policy, 35*(12), 6084-6094. doi: 10.1016/j.enpol.2007.08.020.

Burgess, J., Harrison, C. M., & Filius, P. (1998). Environmental communication and the cultural politics of environmental citizenship. *Environment and planning A, 30*(8), 1445-1460.

Bustamante, M. A., Alburquerque, J. A., Restrepo, A. P., de la Fuente, C., Paredes, C., Moral, R., & Bernal, M. P. (2012). Co-composting of the solid fraction of anaerobic digestates, to obtain added-value materials for use in agriculture. *Biomass and Bioenergy, 43*(0), 26-35. doi: 10.1016/j.biombioe.2012.04.010.

Buytaert, V., Muys, B., Devriendt, N., Pelkmans, L., Kretzschmar, J. G., & Samson, R. (2011). Towards integrated sustainability assessment for energetic use of biomass: A state of the art evaluation of assessment tools. *Renewable and Sustainable Energy Reviews, 15*(8), 3918-3933. doi: 10.1016/j.rser.2011.07.036.

Calvert, K. (2011). Geomatics and bioenergy feasibility assessments: Taking stock and looking forward. *Renewable and Sustainable Energy Reviews, 15*(2), 1117-1124. doi: 10.1016/j.rser.2010.11.014.

Caputo, A. C., Palumbo, M., Pelagagge, P. M., & Scacchia, F. (2005). Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. *Biomass and Bioenergy, 28*(1), 35-51. doi: 10.1016/j.biombioe.2004.04.009.

Carole, T. M., Pellegrino, J., & Paster, M. D. (2004). Opportunities in the industrial biobased products industry. [Research Support, U S Gov't, Non-P H S]. *Appl Biochem Biotechnol, 116*, 871-885.

Carpaneto, E., Chicco, G., Mancarella, P., & Russo, A. (2011). Cogeneration planning under uncertainty. Part II: Decision theory-based assessment of planning alternatives. *Applied Energy, 88*(4), 1075-1083. doi: 10.1016/j.apenergy.2010.08.019.

Caspeta, L., Buijs, N. A. A., & Nielsen, J. (2013). The role of biofuels in the future energy supply. *Energy & Environmental Science, 6*(4), 1077-1082. doi: 10.1039/c3ee24403.

CBS (2012). Huishoudelijk afval per gemeente per inwoner. From http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=80563NED&D1=4,28-31&D2=0,78,299,l&D3=a&HDR=T&STB=G1,G2&VW=T.

Çelikler, D. (2013). Awareness about renewable energy of pre-service science teachers in Turkey. *Renewable Energy, 60*(0), 343-348. doi: 10.1016/j.renene.2013.05.034.

Chau, J., Sowlati, T., Sokhansanj, S., Preto, F., Melin, S., & Bi, X. (2009). Techno-economic analysis of wood biomass boilers for the greenhouse industry. *Applied Energy, 86*(3), 364-371. doi: 10.1016/j.apenergy.2008.05.010.

Cheng, C.-L., Che, P.-Y., Chen, B.-Y., Lee, W.-J., Lin, C.-Y., & Chang, J.-S. (2012). Biobutanol production from agricultural waste by an acclimated mixed bacterial microflora. *Applied Energy, 100*(0), 3-9. doi: 10.1016/j.apenergy.2012.05.042.

Cherubini, F. (2010). The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. *Energy Conversion and Management, 51*(7), 1412-1421. doi: 10.1016/j.enconman.2010.01.015.

Cherubini, F., Jungmeier, G., Wellisch, M., Willke, T., Skiadas, I., Van Ree, R., & de Jong, E. (2009). Toward a common classification approach for biorefinery systems. *Biofuels, Bioproducts and Biorefining, 3*(5), 534-546. doi: 10.1002/bbb.172.

Cherubini, F., & Strømman, A. H. (2011). Life cycle assessment of bioenergy systems: state of the art and future challenges. *Bioresource Technology, 102*(2), 437-451.

Chicco, G., & Mancarella, P. (2009). Distributed multi-generation: A comprehensive view. *Renewable and Sustainable Energy Reviews, 13*(3), 535-551. doi: 10.1016/j.rser.2007.11.014.

Chin, W. W. (1998). The partial least squares approach to structural equation modeling. *Modern methods for business research, 295*(2), 295-336.

Chin, W. W. (2010). How to write up and report PLS analyses *Handbook of partial least squares* (pp. 655-690): Springer.

Chin, W. W., & Newsted, P. R. (1999). Structural equation modeling analysis with small samples using partial least squares. *Statistical strategies for small sample research, 1*(1), 307-341.

Clancy, G., Fröling, M., & Svanström, M. (2013). Changing from petroleum to wood-based materials: critical review of how product sustainability characteristics can be assessed and compared. *Journal of Cleaner Production, 39*, 372-385.

Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*: Routledge Academic.

CREG (2011). International comparison of electricity and gas prices for commerce and industry. Frontier Economics Ltd, London.

DACE (2011). Prijzenboekje. BIM Media BV.

Dagnelie, P., R. Palm, J. Rondeux, & Thill, A. (1985). Tables de cubage des arbres et des peuplements forestiers. *Les presses agronomiques de Gembloux.*

Daianova, L., Dotzauer, E., Thorin, E., & Yan, J. (2012). Evaluation of a regional bioenergy system with local production of biofuel for transportation, integrated with a CHP plant. *Applied Energy, 92*(0), 739-749. doi: 10.1016/j.apenergy.2011.08.016.

Davies, J., Foxall, G. R., & Pallister, J. (2002). Beyond the intention–behaviour mythology an integrated model of recycling. *Marketing theory, 2*(1), 29-113.

De Lange, W. J., Stafford, W. H. L., Forsyth, G. G., & Le Maitre, D. C. (2012). Incorporating stakeholder preferences in the selection of technologies for using invasive alien plants as a bioenergy feedstock: Applying the analytical hierarchy process. *Journal of Environmental Management, 99*(0), 76-83. doi: 10.1016/j.jenvman.2012.01.014.

De Meester, S., Demeyer, J., Velghe, F., Peene, A., Van Langenhove, H., & Dewulf, J. (2012). The environmental sustainability of anaerobic digestion as a biomass valorization technology. *Bioresource Technology, 121*(0), 396-403. doi: 10.1016/j.biortech.2012.06.109.

de Wit, M., & Faaij, A. (2010). European biomass resource potential and costs. *Biomass and Bioenergy, 34*(2), 188-202. doi: 10.1016/j.biombioe.2009.07.011.

Delgado, L., Catarino, A. S., Eder, P., Litten, D., Luo, Z., & Villanueva, A. (2009). End-of-Waste Criteria, Final Report. In J. R. C. European Commission, Institute for Prospective Technological Studies (Ed.), *JRC Scientific and Technical Reports* (pp. 384).

Delivand, M. K., Barz, M., Gheewala, S. H., & Sajjakulnukit, B. (2011). Economic feasibility assessment of rice straw utilization for electricity generating through combustion in Thailand. *Applied Energy, 88*(11), 3651-3658. doi: 10.1016/j.apenergy.2011.04.001.

Delzeit, R., & Kellner, U. (2013). The impact of plant size and location on profitability of biogas plants in Germany under consideration of processing digestates. *Biomass and Bioenergy, 52*(0), 43-53. doi: 10.1016/j.biombioe.2013.02.029.

Demirbas. (2009). Biorefineries for biofuel upgrading: A critical review. *Applied Energy, 86*(0), S151-S161. doi: 10.1016/j.apenergy.2009.04.043.

Devine-Wright, P. (2007). Reconsidering public attitudes and public acceptance of renewable energy technologies: a critical review. *Manchester: School of Environment and Development, University of Manchester. Available at: http://www.sed.manchester.ac.uk/research/beyond_nimbyism*.

Dewulf, J., Bösch, M. E., Meester, B. D., Vorst, G. V. d., Langenhove, H. V., Hellweg, S., & Huijbregts, M. A. J. (2007). Cumulative Exergy Extraction from the Natural Environment (CEENE): a comprehensive Life Cycle Impact Assessment method for resource accounting. *Environmental Science & Technology, 41*(24), 8477-8483. doi: 10.1021/es0711415.

Dewulf, J., Van Langenhove, H., Muys, B., Bruers, S., Bakshi, B. R., Grubb, G. F., … Sciubba, E. (2008). Exergy: Its Potential and Limitations in Environmental Science and Technology. *Environmental Science & Technology, 42*(7), 2221-2232. doi: 10.1021/es071719a.

Dhar, B. R., Nakhla, G., & Ray, M. B. (2012). Techno-economic evaluation of ultrasound and thermal pretreatments for enhanced anaerobic digestion of municipal waste activated sludge. *Waste Management, 32*(3), 542-549. doi: 10.1016/j.wasman.2011.10.007.

Diamantopoulos, A. (1999). Viewpoint–export performance measurement: reflective versus formative indicators. *International Marketing Review, 16*(6), 444-457.

Dixit, A. K., & Pindyck, R. S. (1994). *Investment under uncertainty*. New Jersey: Princeton University Press.

Dowd, A.-M., Itaoka, K., Ashworth, P., Saito, A., & de Best-Waldhober, M. (2014). Investigating the link between knowledge and perception of CO2 and CCS: An international study. *International Journal of Greenhouse Gas Control, 28*(0), 79-87. doi: 10.1016/j.ijggc.2014.06.009.

Dumont, M. (2009). From biogas to green gas. *Upgrading techniques and suppliers*, 6. Retrieved from http://www.rvo.nl/sites/default/files/bijlagen/From%20Biogas%20to%20Green%20Gas%20-%20Upgrading%20techniques%20and%20suppliers.pdf.

EC (1991). Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. From http://europa.eu/legislation_summaries/agriculture/environment/l28013_en.htm.

EC (2004). Towards a European knowledge-based bioeconomy - workshop conclusions on the use of plant biotechnology for the production of industrial biobased products. Brussels.

EC (2006). Directive 2006/12/EC of the European Parliament and of the council of 5 April 2006 on waste. *Official Journal L 2006*(114): 9-21.

EC (2007). COM(2007) 59 final : Communication from the comission to the council and the European Parliament on the Interpretative Communication on waste and by-products.

EC (2008). Directive 2008/98/EC of the European Parliament and of the council of 19 November 2008 on waste and repealing certain Directives. *Official Journal L 2008*(312): 3-30.

EC (2009). Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

EC (2010). COM(2010) 235 final : Communication from the Commission to the Council and the European Parliament on future steps in biowaste management in the European Union. *Brussels (SEC (2010)) 577*.

EC (2010). COM(2010)11 final : Report from the Commission to the Council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling.

EC (2012). COM(2012) 60 : Innovating for Sustainable Growth: A Bioeconomy for Europe.

EEC (1975). Council Directive of 15 July 1975 on waste (75/442/EEC). *Official Journal L*. *1975*: 39.

EEX (2013). EU emission allowances. From http://www.eex.com/en/Market%20Data/Trading%20Data/Emission%20Rights/EU%20Emission%20Allowances%20%7C%20Spot.

Ekvall, T., & Finnveden, G. (2001). Allocation in ISO 14041—a critical review. *Journal of Cleaner Production, 9*(3), 197-208.

Esso. Red diesel price. from http://www.truckstopbelgie.be.

Faaij, A., Steetskamp, I., van Wijk, A., & Turkenburg, W. (1997). Exploration of the land potential for the production of biomass for energy in the Netherlands. *Biomass and Bioenergy, 14*(5-6), 439-456. doi: 10.1016/s0961-9534(98)00002-6.

Fazio, S., & Monti, A. (2011). Life cycle assessment of different bioenergy production systems including perennial and annual crops. *Biomass and Bioenergy, 35*(12), 4868-4878. doi: 10.1016/j.biombioe.2011.10.014.

Fell, M. J., & Chiu, L. F. (2014). Children, parents and home energy use: Exploring motivations and limits to energy demand reduction. *Energy Policy, 65*(0), 351-358. doi: 10.1016/j.enpol.2013.10.003.

Fernandes, U., & Costa, M. (2010). Potential of biomass residues for energy production and utilization in a region of Portugal. *Biomass and Bioenergy, 34*(5), 661-666. doi: 10.1016/j.biombioe.2010.01.009.

Fiala, M., Pellizzi, G., & Riva, G. (1997). A Model for the Optimal Dimensioning of Biomass-fuelled Electric Power Plants. *Journal of Agricultural Engineering Research, 67*(1), 17-25. doi: 10.1006/jaer.1996.0142.

Fiorese, G., & Guariso, G. (2010). A GIS-based approach to evaluate biomass potential from energy crops at regional scale. *Environmental Modelling & Software, 25*(6), 702-711. doi: 10.1016/j.envsoft.2009.11.008.

Fischhoff, B., Slovic, P., & Lichtenstein, S. (1980). *Knowing what you want: Measuring labile values*. Paper presented at the T. Wallsten (Ed.), Cognitive processes in choice and decision behavior, Hillsdale, NJ.

Forman, E., & Peniwati, K. (1998). Aggregating individual judgments and priorities with the analytic hierarchy process. *European Journal of Operational Research, 108*(1), 165-169. doi: 10.1016/s0377-2217(97)00244-0.

Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of marketing research*, 39-50.

Freppaz, D., Minciardi, R., Robba, M., Rovatti, M., Sacile, R., & Taramasso, A. (2004). Optimizing forest biomass exploitation for energy supply at a regional level. *Biomass and Bioenergy, 26*(1), 15-25. doi: 10.1016/s0961-9534(03)00079-5.

Freudenberg, M. (2003). Composite Indicators of Country Performance: a critical assessment *Technology and Industry Working Papers*. Paris: OECD.

Gan, J. (2007). Supply of biomass, bioenergy, and carbon mitigation: Method and application. *Energy Policy, 35*(12), 6003-6009. doi: 10.1016/j.enpol.2007.08.014.

Garofalo, R. (2010). AquaFUELS: Deliverables 3.3 and 3.5: Life-cycle assessment and environmental assessment. From http://www.aquafuels.eu/attachments/079_D%203.3-3.5%20Life-Cycle%20Assessment%20and%20Environmental%20Assessment.pdf.

Gasparatos, A., El-Haram, M., & Horner, M. (2008). A critical review of reductionist approaches for assessing the progress towards sustainability. *Environmental Impact Assessment Review, 28*(4–5), 286-311. doi: 10.1016/j.eiar.2007.09.002.

Gasparatos, A., & Scolobig, A. (2012). Choosing the most appropriate sustainability assessment tool. *Ecological Economics, 80*(0), 1-7. doi: 10.1016/j.ecolecon.2012.05.005.

Gebrezgabher, S. A., Meuwissen, M. P. M., Prins, B. A. M., & Lansink, A. G. J. M. O. (2010). Economic analysis of anaerobic digestion--A case of Green power biogas plant in The Netherlands. *NJAS - Wageningen Journal of Life Sciences, 57*(2), 109-115. doi: 10.1016/j.njas.2009.07.006.

Geisser, S. (1974). A predictive approach to the random effect model. *Biometrika, 61*(1), 101-107.

Ghatak, H. R. (2011). Biorefineries from the perspective of sustainability: Feedstocks, products, and processes. *Renewable and Sustainable Energy Reviews, 15*(8), 4042-4052. doi: 10.1016/j.rser.2011.07.034.

Gold, S., & Seuring, S. (2011). Supply chain and logistics issues of bioenergy production. *Journal of Cleaner Production, 19*(1), 32-42. doi: 10.1016/j.jclepro.2010.08.009.

Gómez, A., Rodrigues, M., Montañés, C., Dopazo, C., & Fueyo, N. (2010). The potential for electricity generation from crop and forestry residues in Spain. *Biomass and Bioenergy, 34*(5), 703-719. doi: 10.1016/j.biombioe.2010.01.013.

Goorix, L. and A. Meijnders (2003). Contexteffecten bij de beoordeling van biomassa: de modererende rol van attitudesterkte bij assimilatie en contrasteffecten.

Gossling, S., Kunkel, T., Schumacher, K., Heck, N., Birkemeyer, J., Froese, J., … Schliermann, E. (2005). A target group-specific approach to "green" power retailing: students as consumers of renewable energy. *Renewable and Sustainable Energy Reviews, 9*(1), 69-83.

Götz, O., Liehr-Gobbers, K., & Krafft, M. (2010). Evaluation of structural equation models using the partial least squares (PLS) approach *Handbook of partial least squares* (pp. 691-711): Springer.

Graham, R. L., English, B. C., & Noon, C. E. (2000). A Geographic Information System-based modeling system for evaluating the cost of delivered energy crop feedstock. *Biomass and Bioenergy, 18*(4), 309-329. doi: 10.1016/s0961-9534(99)00098-7.

Grigoroudis, E., Petridis, K., & Arabatzis, G. (2014). RDEA: A recursive DEA based algorithm for the optimal design of biomass supply chain networks. *Renewable Energy, 71*(0), 113-122. doi: 10.1016/j.renene.2014.05.001.

Groengasnl (2012). Biotickets voor groen gas. From http://groengas.nl/wp-content/uploads/2013/02/2012-09-00-Biotickets-voor-groen-gas.pdf.

Guisson, R. and M. Van Dael (2013). Energy Conversion Park – A concept for the efficient use of regionally available biomass residue streams. *Waste Management 33*(8): 1689-1690.

Haddad, M. A., & Anderson, P. F. (2008). A GIS methodology to identify potential corn stover collection locations. *Biomass and Bioenergy, 32*(12), 1097-1108. doi: 10.1016/j.biombioe.2008.02.007.

Haimes, Y. Y. (2004). *Risk modeling, assessment, and management*. Hoboken (New Jersey): John Wiley & Sons.

Hair Jr, J. F., Hult, G. T. M., Ringle, C., & Sarstedt, M. (2013). *A primer on partial least squares structural equation modeling (PLS-SEM)*: SAGE Publications, Incorporated.

Halder, P., Havu-Nuutinen, S., Pietarinen, J., & Pelkonen, P. (2011). Bioenergy and youth: Analyzing the role of school, home, and media from the future policy perspectives. *Applied Energy, 88*(4), 1233-1240. doi: 10.1016/j.apenergy.2010.10.017.

Halder, P., Pietarinen, J., Havu-Nuutinen, S., & Pelkonen, P. (2010). Young citizens' knowledge and perceptions of bioenergy and future policy implications. *Energy Policy, 38*(6), 3058-3066. doi: 10.1016/j.enpol.2010.01.046.

Hayton, J. C., Allen, D. G., & Scarpello, V. (2004). Factor Retention Decisions in Exploratory Factor Analysis: a Tutorial on Parallel Analysis. *Organizational Research Methods, 7*(2), 191-205. doi: 10.1177/1094428104263675.

Helble, A., & Möbius, C. (2008). Comparing aerobic and anaerobic wastewater treatment processes for papermill effluent considering new developments. Wiesbaden: cm-consult.

Hennecke, A. M., Faist, M., Reinhardt, J., Junquera, V., Neeft, J., & Fehrenbach, H. (2013). Biofuel greenhouse gas calculations under the European Renewable Energy Directive – A comparison of the BioGrace tool vs. the tool of the Roundtable on Sustainable Biofuels. *Applied Energy, 102*(0), 55-62. doi: 10.1016/j.apenergy.2012.04.020.

Henseler, J. (2012). PLS-MGA: A Non-Parametric Approach to Partial Least Squares-based Multigroup Analysis. In W. A. Gaul, A. Geyer-Schulz, L. Schmidt-Thieme & J. Kunze (Eds.), *Challenges at the Interface of Data Analysis, Computer Science, and Optimization* (pp. 495-501): Springer Berlin Heidelberg.

Hilkiah Igoni, A., Ayotamuno, M. J., Eze, C. L., Ogaji, S. O. T., & Probert, S. D. (2008). Designs of anaerobic digesters for producing biogas from municipal solid-waste. *Applied Energy, 85*(6), 430-438. doi: 10.1016/j.apenergy.2007.07.013.

Himadri Roy, G. (2011). Biorefineries from the perspective of sustainability: Feedstocks, products, and processes. *Renewable and Sustainable Energy Reviews, 15*(8), 4042-4052. doi: 10.1016/j.rser.2011.07.034.

Hobbs, B. F., Chankong, V., Hamadeh, W., & Stakhiv, E. Z. (1992). Does choice of multicriteria method matter? An experiment in water resources planning. *Water Resour. Res., 28*(7), 1767-1779. doi: 10.1029/92wr00712.

Hobbs, B. F., & Horn, G. T. F. (1997). Building public confidence in energy planning: a multimethod MCDM approach to demand-side planning at BC gas. *Energy Policy, 25*(3), 357-375. doi: 10.1016/s0301-4215(97)00025-6.

Hobbs, B. F., & Meier, P. (2000). Energy decisions and the environment: a guide to the use of multicriteria methods.

Hobman, E. V., & Ashworth, P. (2013). Public support for energy sources and related technologies: The impact of simple information provision. *Energy Policy, 63*(0), 862-869. doi: 10.1016/j.enpol.2013.09.011.

Höhn, J., Lehtonen, E., Rasi, S., & Rintala, J. (2014). A Geographical Information System (GIS) based methodology for determination of potential biomasses and sites for biogas plants in southern Finland. *Applied Energy, 113*(0), 1-10. doi: 10.1016/j.apenergy.2013.07.005.

Holm-Nielsen, J. B., Al Seadi, T., & Oleskowicz-Popiel, P. (2009). The future of anaerobic digestion and biogas utilization. *Bioresource Technology, 100*(22), 5478-5484. doi: 10.1016/j.biortech.2008.12.046.

Holma, A., Koponen, K., Antikainen, R., Lardon, L., Leskinen, P., & Roux, P. (2013). Current limits of life cycle assessment framework in evaluating environmental sustainability–case of two evolving biofuel technologies. *Journal of Cleaner Production, 54*, 215-228.

Hoogsteen, R., Braber, K., & Smit, R. (2003). Haalbaarheid warmtenet regio Twente (pp. 68). Arnhem: KEMA.

Hoop, J. d., Daatselaar, C., Doornewaard, G., & Tomson, N. (2011). Mineralenconcentraten uit mest - Economische analyse en gebruikerservaringen uit de pilots mestverwerking in 2009 en 2010. Wageningen: Wageningen UR.

Howell, R., Shackley, S., Mabon, L., Ashworth, P., & Jeanneret, T. (2014). Engaging the public with low-carbon energy technologies: Results from a Scottish large group process. *Energy Policy, 66*(0), 496-506. doi: 10.1016/j.enpol.2013.11.041.

Hwang, C. L. and K. Yoon (1981). Multiple attribute decision making - methods and applications. Berlin Heidelberg New-York, Springer-Verlag.

Iakovou, E., Karagiannidis, A., Vlachos, D., Toka, A., & Malamakis, A. (2010). Waste biomass-to-energy supply chain management: A critical synthesis. *Waste Management, 30*(10), 1860-1870. doi: 10.1016/j.wasman.2010.02.030.

IEA (2012). World Energy Outlook 2012. IEA Publications. From www.iea.org.

Igliński, B., Buczkowski, R., Iglińska, A., Cichosz, M., Piechota, G., & Kujawski, W. (2012). Agricultural biogas plants in Poland: Investment process, economical and environmental aspects, biogas potential. *Renewable and Sustainable Energy Reviews, 16*(7), 4890-4900. doi: 10.1016/j.rser.2012.04.037.

IPTS. (2013). Study report on End-of-waste criteria for Biodegradable waste subjected to biological treatment, Draft Final Report In IPTS (Ed.). Seville, Spain.

Jalilova, G., Khadka, C., & Vacik, H. (2012). Developing criteria and indicators for evaluating sustainable forest management: A case study in Kyrgyzstan. *Forest Policy and Economics, 21*(0), 32-43. doi: 10.1016/j.forpol.2012.01.010.

Jarvis, C. B., MacKenzie, S. B., & Podsakoff, P. M. (2003). A critical review of construct indicators and measurement model misspecification in marketing and consumer research. *Journal of consumer research, 30*(2), 199-218.

Jeffreys, I. (2004). The use of compensatory and non-compensatory multicriteria analysis for small-scale forestry. *Small-scale Forest Economics, Management and Policy, 3*(1), 99-117. doi: 10.1007/s11842-004-0007-0.

Jia, J. and G. W. Fischer (1993). Evaluating multiattribute decision quality: a simulation study' presented at the ORSA/TIMS joint national meeting.

Joerin, F., & Musy, A. (2000). Land management with GIS and multicriteria analysis. *International Transactions in Operational Research, 7*(1), 67-78. doi: 10.1016/s0969-6016(99)00028-3.

JRC (2011). Technical Assessment of the Renewable Energy Action Plans. Luxembourg.

Kaditi, E. A. (2009). Bioenergy policies in a global context. *Journal of Cleaner Production, 17*, S4-S8.

Kaldellis, J. K., Kapsali, M., & Katsanou, E. (2012). Renewable energy applications in Greece—What is the public attitude? *Energy Policy, 42*(0), 37-48. doi: 10.1016/j.enpol.2011.11.017.

Kalt, G., & Kranzl, L. (2011). Assessing the economic efficiency of bioenergy technologies in climate mitigation and fossil fuel replacement in Austria using a techno-economic approach. *Applied Energy, 88*(11), 3665-3684. doi: 10.1016/j.apenergy.2011.03.014.

Kantor, M., Wajda, K., Lannoo, B., Casier, K., Verbrugge, S., Pickavet, M., . . . Mitcsenkov, A. (2010, June 27 2010-July 1 2010). *General framework for techno-economic analysis of next generation access networks.* Paper presented at the 12th International Conference on Transparent Optical Networks (ICTON).

Kapassa, M., Abeliotis, K., & Scoullos, M. (2013). Knowledge, beliefs and attitudes of secondary school students on renewable feedstocks/biomass: the case of Greece. *Environment, Development and Sustainability, 15*(1), 101-116.

Karaj, S., Rehl, T., Leis, H., & Müller, J. (2010). Analysis of biomass residues potential for electrical energy generation in Albania. *Renewable and Sustainable Energy Reviews, 14*(1), 493-499. doi: 10.1016/j.rser.2009.07.026.

Karatepe, Y., Neşe, S. V., Keçebaş, A., & Yumurtacı, M. (2012). The levels of awareness about the renewable energy sources of university students in Turkey. *Renewable Energy, 44*(0), 174-179. doi: 10.1016/j.renene.2012.01.099.

Karellas, S., Boukis, I., & Kontopoulos, G. (2010). Development of an investment decision tool for biogas production from agricultural waste. *Renewable and Sustainable Energy Reviews, 14*(4), 1273-1282. doi: 10.1016/j.rser.2009.12.002.

Karlis, D., Saporta, G., & Spinakis, A. (2003). A simple rule for the selection of principal components. *Communications in Statistics-Theory and Methods, 32*(3), 643-666.

Kollmuss, A., & Agyeman, J. (2002). Mind the gap: why do people act environmentally and what are the barriers to pro-environmental behavior? *Environmental education research, 8*(3), 239-260.

Kowalski, K., Stagl, S., Madlener, R., & Omann, I. (2009). Sustainable energy futures: Methodological challenges in combining scenarios and participatory multicriteria analysis. *European Journal of Operational Research, 197*(3), 1063-1074. doi: DOI 10.1016/j.ejor.2007.12.049.

Kravanja, P., Modarresi, A., & Friedl, A. (2013). Heat integration of biochemical ethanol production from straw - A case study. *Applied Energy, 102*(0), 32-43. doi: DOI 10.1016/j.apenergy.2012.08.014.

Kuppens, M., Umans, L., Snijkers, T., Werquin, W., Thibau, B., Smeets, K., & Vangilbergen, B. (2011). Tariven en capaciteiten voor storten en verbranden. Acualisatie tot 2009, evolutie en prognose. Mechelen: OVAM.

Kuppens, T. (2012). *Techno-economic assessment of fast pyrolysis for the valorisation of short rotation coppice cultivated for phytoextraction*. PhD Dissertation, Hasselt University.

Kuyper, Linnemans, & Hesselink, K. (2011). Eindrapportage Grasraffinage in Oostelijk Flevoland - een businessplan (pp. 26): Ekwadraat advies.

Lahdelma, R., Salminen, P., & Hokkanen, J. (2000). Using Multicriteria Methods in Environmental Planning and Management. *Environmental Management, 26*(6), 595-605. doi: 10.1007/s002670010118.

Langeveld, H., Meeusen, M., & Sanders, J. (2010). *The biobased economy : biofuels, materials and chemicals in the post-oil era*. London; Washington, DC: Earthscan.

Lantz, M. (2012). The economic performance of combined heat and power from biogas produced from manure in Sweden – A comparison of different CHP technologies. *Applied Energy, 98*(0), 502-511. doi: 10.1016/j.apenergy.2012.04.015.

Lensink. (2012). Basisbedragen in de SDE+ 2013. From http://www.ecn.nl/docs/library/report/2012/e12038.pdf.

Lensink, S., Wassenaar, J., Mozaffarian, M., Luxembourg, S., & Faasen, C. (2011). Basisbedragen in de SDE+ 2012. From http://www.ecn.nl/docs/library/report/2011/e11054.pdf.

Levy, H., & Sarnat, M. (1994). *Capital investment and financial decisions*: Prentice Hall.

Løken, E. (2007). Use of multicriteria decision analysis methods for energy planning problems. *Renewable and Sustainable Energy Reviews, 11*(7), 1584-1595. doi: 10.1016/j.rser.2005.11.005.

López, M., Soliva, M., Martínez-Farré, F. X., Fernández, M., & Huerta-Pujol, O. (2010). Evaluation of MSW organic fraction for composting: Separate collection or mechanical sorting. *Resources, Conservation and Recycling, 54*(4), 222-228. doi: 10.1016/j.resconrec.2009.08.003.

Lorie, J. H., & Savage, L. J. (1955). Three problems in rationing capital. *Journal of Business, 28***.**

Ma, J., Scott, N. R., DeGloria, S. D., & Lembo, A. J. (2005). Siting analysis of farm-based centralized anaerobic digester systems for distributed generation using GIS. *Biomass and Bioenergy, 28*(6), 591-600. doi: 10.1016/j.biombioe.2004.12.003.

Maarten, C. (2012). *Een verkennend onderzoek naar de economische waarde van pyrolyseolie uit korteomloophout.* Master thesis, Hasselt University.

MacKenzie, S. B., Podsakoff, P. M., & Jarvis, C. B. (2005). The problem of measurement model misspecification in behavioral and organizational research and some recommended solutions. *Journal of Applied Psychology, 90*(4), 710.

Maes, D., & Van Passel, S. (2014). Advantages and limitations of exergy indicators to assess sustainability of bioenergy and biobased materials. *Environmental Impact Assessment Review, 45*, 19-29.

Manley, J. B., Anastas, P. T., & Cue Jr, B. W. (2008). Frontiers in Green Chemistry: meeting the grand challenges for sustainability in R&D and manufacturing. *Journal of Cleaner Production, 16*(6), 743-750. doi: 10.1016/j.jclepro.2007.02.025.

Marchetti, J. M., Miguel, V. U., & Errazu, A. F. (2008). Techno-economic study of different alternatives for biodiesel production. *Fuel Processing Technology, 89*(8), 740-748. doi: 10.1016/j.fuproc.2008.01.007.

Márquez, N., Reumerman, P., Venselaar, J., Broeze, J., & Pelkmans, L. (2012). *Biomass Based Energy Conversion Parks: A Multidimensional Approach for Efficient Use of Biomass.* Paper presented at the 20th European Biomass Conference and Exhibition, Milano.

McCormick, K. (2010). Communicating bioenergy: a growing challenge. *Biofuels, Bioproducts and Biorefining, 4*(5), 494-502. doi: 10.1002/bbb.243.

Menrad, K., Klein, A., & Kurka, S. (2009). Interest of industrial actors in biorefinery concepts in Europe. *Biofuels, Bioproducts and Biorefining, 3*(3), 384-394. doi: 10.1002/bbb.144.

Methanex (2012). Methanol price. From http://www.methanex.com/products/methanolprice.html.

Ministerie Economische Zaken, Landbouw en Innovatie (2008). Regeling van de Minister van Economische Zaken van 28 februari 2008, nr. WJZ 8024263, tot vaststelling van algemene uitvoeringsregels voor de subsidieverstrekking op grond van het Besluit stimulering duurzame energieproductie (Algemene uitvoeringsregeling stimulering duurzame energieproductie). The Netherlands.

Ministerie Infrastructuur en Milieu (1986). Wet bodembescherming van 3 juli 1986. The Netherlands.

Moorkens, I. and K. Briffaerts (2009). Onrendabele toppen groene warmte. From http://www2.vlaanderen.be/economie/energiesparen/milieuvriendelijke/Cijfers&statistieken/Rapport_OT_groenewarmte_2009.pdf.

Murphy, J. D., & McKeogh, E. (2004). Technical, economic and environmental analysis of energy production from municipal solid waste. *Renewable Energy, 29*(7), 1043-1057. doi: 10.1016/j.renene.2003.12.002.

Murphy, J. D., McKeogh, E., & Kiely, G. (2004). Technical/economic/environmental analysis of biogas utilisation. *Applied Energy, 77*(4), 407-427. doi: 10.1016/j.apenergy.2003.07.005.

Mysiak, J. (2006). Consistency of the results of different MCA methods: a critical review. *Environment and Planning C-Government and Policy, 24*(2), 257-277. doi: Doi 10.1068/C04103s.

NABC. (2011). Techno-economic Analysis: Evaluating the Economic Viability and Potential of the NABC Process Strategies. Retrieved from www.nabcprojects.org/pdfs/techno-economic_analysis_evaluating_economic_viability.pdf.

Nameghi, E. N., & Shadi, M. (2013). Affective and cognitive: Consumers attitude toward practicing green (reducing, recycling & reusing). *International Journal of Marketing Studies, 5*(1), p157.

Neijens, P., De Ridder, J., & Saris, W. (1992). An instrument for collecting informed opinions. *Quality and Quantity, 26*(3), 245-258. doi: 10.1007/bf00172428.

Ng, K. S., & Sadhukhan, J. (2011). Process integration and economic analysis of bio-oil platform for the production of methanol and combined heat and power. *Biomass and Bioenergy, 35*(3), 1153-1169. doi: 10.1016/j.biombioe.2010.12.003.

Nilsson, D., & Hansson, P. A. (2001). Influence of various machinery combinations, fuel proportions and storage capacities on costs for co-handling of straw and reed canary grass to district heating plants. *Biomass and Bioenergy, 20*(4), 247-260. doi: 10.1016/s0961-9534(00)00077-5.

Nizami, A.-S., & Murphy, J. D. (2010). What type of digester configurations should be employed to produce biomethane from grass silage? *Renewable and Sustainable Energy Reviews, 14*(6), 1558-1568. doi: 10.1016/j.rser.2010.02.006.

Nunnally, J., & Bernstein, I. (1994). Psychometric Theory (3) McGraw-Hill. *New York*.

Nzihou, A., & Stanmore, B. (2013). The fate of heavy metals during combustion and gasification of contaminated biomass–A brief review. *Journal of Hazardous Materials*, 56–66.

O'connor, B. (2000). SPSS and SAS programs for determining the number of components using parallel analysis and Velicer's MAP test. *Behavior Research Methods, Instruments, & Computers, 32*(3), 396-402. doi: 10.3758/bf03200807.

O'Keeffe, S., Schulte, R. P. O., Sanders, J. P. M., & Struik, P. C. (2011). I. Technical assessment for first generation green biorefinery (GBR) using mass and energy balances: Scenarios for an Irish GBR blueprint. *Biomass and Bioenergy, 35*(11), 4712-4723. doi: 10.1016/j.biombioe.2011.06.017.

O'Keeffe, S., Schulte, R. P. O., Sanders, J. P. M., & Struik, P. C. (2012). II. Economic assessment for first generation green biorefinery (GBR): Scenarios for an Irish GBR blueprint. *Biomass and Bioenergy, 41*(0), 1-13. doi: 10.1016/j.biombioe.2011.11.018.

Odlare, M., Arthurson, V., Pell, M., Svensson, K., Nehrenheim, E., & Abubaker, J. (2011). Land application of organic waste – Effects on the soil ecosystem. *Applied Energy, 88*(6), 2210-2218. doi: 10.1016/j.apenergy.2010.12.043.

Panichelli, L., & Gnansounou, E. (2008). GIS-based approach for defining bioenergy facilities location: A case study in Northern Spain based on marginal delivery costs and resources competition between facilities. *Biomass and Bioenergy, 32*(4), 289-300. doi: 10.1016/j.biombioe.2007.10.008.

Panoutsou, C., Eleftheriadis, J., & Nikolaou, A. (2009). Biomass supply in EU27 from 2010 to 2030. *Energy Policy, 37*(12), 5675-5686. doi: DOI 10.1016/j.enpol.2009.08.032.

Papadopoulos, A., & Karagiannidis, A. (2008). Application of the multicriteria analysis method Electre III for the optimisation of decentralised energy systems. *Omega, 36*(5), 766-776. doi: DOI: 10.1016/j.omega.2006.01.004.

Papadopoulos, D. P., & Katsigiannis, P. A. (2002). Biomass energy surveying and techno-economic assessment of suitable CHP system installations. *Biomass and Bioenergy, 22*(2), 105-124. doi: 10.1016/s0961-9534(01)00064-2.

Peck, P., Bennett, S. J., Bissett-Amess, R., Lenhart, J., & Mozaffarian, H. (2009). Examining understanding, acceptance, and support for the biorefinery concept among EU policy-makers. *Biofuels, Bioproducts and Biorefining, 3*(3), 361-383. doi: 10.1002/bbb.154.

Perlaviciute, G., & Steg, L. (2014). Contextual and psychological factors shaping evaluations and acceptability of energy alternatives: Integrated review and research agenda. *Renewable and Sustainable Energy Reviews, 35*, 361-381.

Pick, D., Dieterich, M., & Heintschel, S. (2012). Biogas Production Potential from Economically Usable Green Waste. *Sustainability, 4*(4), 682-702.

Pohekar, S. D., & Ramachandran, M. (2004). Application of multicriteria decision making to sustainable energy planning--A review. *Renewable and Sustainable Energy Reviews, 8*(4), 365-381. doi: 10.1016/j.rser.2003.12.007.

Polonsky, M. J., Vocino, A., Grau, S. L., Garma, R., & Ferdous, A. S. (2012). The impact of general and carbon-related environmental knowledge on attitudes and behaviour of US consumers. *Journal of Marketing Management, 28*(3-4), 238-263.

Preacher, K. J., & Hayes, A. F. (2008). Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behavior research methods, 40*(3), 879-891.

Qu, M., Ahponen, P., Tahvanainen, L., Gritten, D., Mola-Yudego, B., & Pelkonen, P. (2011). Chinese university students' knowledge and attitudes regarding forest bioenergy. *Renewable and Sustainable Energy Reviews, 15*(8), 3649-3657.

Qu, M., Ahponen, P., Tahvanainen, L., Gritten, D., Mola-Yudego, B., & Pelkonen, P. (2012). Practices and perceptions on the development of forest bioenergy in China from participants in national forestry training courses. *Biomass and Bioenergy, 40*(0), 53-62. doi: 10.1016/j.biombioe.2012.01.050.

Rajecki, D. (1982). Attitudes: themes and advances. Sunderland MA, Sinauer Associates Inc.

Ramírez, C. A., & Worrell, E. (2006). Feeding fossil fuels to the soil: An analysis of energy embedded and technological learning in the fertilizer industry. *Resources, Conservation and Recycling, 46*(1), 75-93. doi: 10.1016/j.resconrec.2005.06.004.

Rapport, J., Zhang, R., Jenkins, B., & Williams, R. (2008). Current Anaerobic Digestion Technologies Used for Treatment of Municipal Organic Solid Waste: California Integrated Waste Management Board.

Rebitanim, N. Z., Wan Ab Karim Ghani, W. A., Rebitanim, N. A., & Amran Mohd Salleh, M. (2013). Potential applications of wastes from energy generation particularly biochar in Malaysia. *Renewable and Sustainable Energy Reviews, 21*(0), 694-702. doi: 10.1016/j.rser.2012.12.051.

Reinartz, W., Krafft, M., & Hoyer, W. D. (2004). The customer relationship management process: its measurement and impact on performance. *Journal of marketing research, 41*(3), 293-305.

Reinhard, S., Knox Lovell, C., & Thijssen, G. J. (2000). Environmental efficiency with multiple environmentally detrimental variables; estimated with SFA and DEA. *European Journal of Operational Research, 121*(2), 287-303.

Riet, J.v. (2011). Duurzame verwerking gemeentelijke biomassastromen. Samenwerkingsverband Regio Eindhoven.

Rijksoverheid (2012). Mestbeleid. Retrieved June 11, 2012, from http://www.rijksoverheid.nl/onderwerpen/mest/mestbeleid.

Roe, N. E., Stoffella, P. J., & Graetz, D. (1997). Composts from Various Municipal Solid Waste Feedstocks Affect Vegetable Crops. I. Emergence and Seedling Growth. *Journal of the American Society for Horticultural Science, 122*(3), 427-432.

Rogers, J. G., & Brammer, J. G. (2012). Estimation of the production cost of fast pyrolysis bio-oil. *Biomass and Bioenergy, 36*(0), 208-217. doi: 10.1016/j.biombioe.2011.10.028.

Rösch, C., & Kaltschmitt, M. (1999). Energy from biomass—do non-technical barriers prevent an increased use? *Biomass and Bioenergy, 16*(5), 347-356. doi: 10.1016/S0961-9534(98)00088-9.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *Int. J. Services Sciences, 1*(1), 16.

Sahmer, K., Hanafi, M., & El Qannari, M. (2006). Assessing Unidimensionality within PLS Path Modeling Framework. In M. Spiliopoulou, R. Kruse, C. Borgelt, A. Nürnberger & W. Gaul (Eds.), *From Data and Information Analysis to Knowledge Engineering* (pp. 222-229): Springer Berlin Heidelberg.

Saidur, R., Abdelaziz, E. A., Demirbas, A., Hossain, M. S., & Mekhilef, S. (2011). A review on biomass as a fuel for boilers. *Renewable and Sustainable Energy Reviews, 15*(5), 2262-2289. doi: 10.1016/j.rser.2011.02.015.

Scarlat, N., & Dallemand, J.-F. (2011). Recent developments of biofuels/bioenergy sustainability certification: A global overview. *Energy Policy, 39*(3), 1630-1646. doi: 10.1016/j.enpol.2010.12.039.

Schlager, P., Krismann, A., & Schmieder, K. (2010). *Estimating the biomass potential of wooden landscape components for energy production in Schwäbisch Hall (Germany)*. Paper presented at the ISEE 2010, Oldenburg-Bremen.

Segon, V., Støer, D., Domac, J., & Yang, K. (2004). Raising the awareness of bioenergy benefits: results of two public surveys on attitudes, perceptions and knowledge. In I. B. T. Report (Ed.), (pp. 1-4).

Shi, X., Elmore, A., Li, X., Gorence, N. J., Jin, H., Zhang, X., & Wang, F. (2008). Using spatial information technologies to select sites for biomass power plants: A case study in Guangdong Province, China. *Biomass and Bioenergy, 32*(1), 35-43. doi: 10.1016/j.biombioe.2007.06.008.

Silveira, S. (2005). How to Realize the Bioenergy Prospects? In S. Dr Semida (Ed.), *Bioenergy - Realizing the Potential* (pp. 3-17). Oxford: Elsevier.

Simcock, N., MacGregor, S., Catney, P., Dobson, A., Ormerod, M., Robinson, Z., …Marie Hall, S. (2014). Factors influencing perceptions of domestic energy information: Content, source and process. *Energy Policy, 65*, 455-464.

Singh, R. K., Murty, H., Gupta, S., & Dikshit, A. (2009). An overview of sustainability assessment methodologies. *Ecological indicators, 9*(2), 189-212.

Singh, R. P., Tyagi, V. V., Allen, T., Ibrahim, M. H., & Kothari, R. (2011). An overview for exploring the possibilities of energy generation from municipal solid waste (MSW) in Indian scenario. *Renewable and Sustainable Energy Reviews, 15*(9), 4797-4808. doi: 10.1016/j.rser.2011.07.071.

Smeets, E. M. W., Faaij, A. P. C., Lewandowski, I. M., & Turkenburg, W. C. (2007). A bottom-up assessment and review of global bioenergy potentials to 2050. *Progress in Energy and Combustion Science, 33*(1), 56-106. doi: 10.1016/j.pecs.2006.08.001.

Smura, T., Kiiski, A., & Hämmäinen, H. (2007). Virtual operators in the mobile industry: a techno-economic analysis. *NETNOMICS: Economic Research and Electronic Networking, 8*(1-2), 25-48. doi: 10.1007/s11066-008-9012-3.

Soimakallio, S., & Koponen, K. (2011). How to ensure greenhouse gas emission reductions by increasing the use of biofuels? – Suitability of the European Union sustainability criteria. *Biomass and Bioenergy, 35*(8), 3504-3513. doi: 10.1016/j.biombioe.2011.04.041.

Song, H., Starfelt, F., Daianova, L., & Yan, J. (2012). Influence of drying process on the biomass-based polygeneration system of bioethanol, power and heat. *Applied Energy, 90*(1), 32-37. doi: 10.1016/j.apenergy.2011.02.019.

Spinney, P. J., & Watkins, G. C. (1996). Monte Carlo simulation techniques and electric utility resource decisions. *Energy Policy, 24*(2), 155-163. doi: 10.1016/0301-4215(95)00094-1.

Srirangan, K., Akawi, L., Moo-Young, M., & Chou, C. P. (2012). Towards sustainable production of clean energy carriers from biomass resources. *Applied Energy, 100*(0), 172-186. doi: 10.1016/j.apenergy.2012.05.012.

Staatsblad (2007). Besluit van 16 oktober 2007 houdende regels inzake de verstrekking van subsidies ten behoeve van de productie van hernieuwbare elektriciteit, hernieuwbaar gas en elektriciteit opgewekt door middel van warmtekrachtkoppeling (Besluit stimulering duurzame energieproductie).

Staatsblad (2011). Regeling van de Staatssecretaris van Infrastructuur en Milieu van 2 mei 2011, nr. BJZ2011044006, houdende nadere regels met betrekking tot energie uit hernieuwbare bronnen voor vervoer (Regeling hernieuwbare energie vervoer).

Starkl, M., & Brunner, N. (2004). Feasibility versus sustainability in urban water management. *Journal of Environmental Management, 71*(3), 245-260. doi: 10.1016/j.jenvman.2004.03.004.

Starr, K., Gabarrell, X., Villalba, G., Talens Peiro, L., & Lombardi, L. (2014). Potential CO2 savings through biomethane generation from municipal waste biogas. *Biomass and Bioenergy, 62*(0), 8-16. doi: 10.1016/j.biombioe.2014.01.023.

Stewart, T. J. A critical survey on the status of multiple criteria decision making theory and practice. *Omega, 20*(5-6), 569-586. doi: 10.1016/0305-0483(92)90003-p.

Stoney, S. M., Tomlins, B., Morris, M. B., Economic, Social Research Council , S., & Council, S. R. (1995). *Environmental Education: Teaching Approaches and Students' Attitudes*: Economic and Social Research Council.

Stroobandt, A. (2007). Personal communication. Cogen Vlaanderen vzw (platform for CHP).

Sudarmadi, S., Suzuki, S., Kawada, T., Netti, H., Soemantri, S., & Tri Tugaswati, A. (2001). A Survey of Perception, Knowledge, Awareness, and attitude in Regard to Environmental Problems in a Sample of two Different Social Groups in Jakarta, Indonesia. *Environment, Development and Sustainability, 3*(2), 169-183. doi: 10.1023/a:1011633729185.

Szargut, J. (2005). *Exergy Method, Technical and Ecological Applications*. Gateshead: WIT Press.

Szargut, J., Morris, D., & Steward, F. (1988). *Exergy analysis of thermal, chemical and metallurgical processes* Berlin: Hemisphere Puhl Corp, New York/Springer Verlag.

Tagashira, N., & Senda, Y. (2011). What information should be provided in communications on biomass power generation? *Applied Energy, 88*(7), 2519-2529. doi: 10.1016/j.apenergy.2011.01.020.

Tenenhaus, M., Vinzi, V. E., Chatelin, Y.-M., & Lauro, C. (2005). PLS path modeling. *Computational statistics & data analysis, 48*(1), 159-205.

Ter Mors, E., Weenig, M. W. H., Ellemers, N., & Daamen, D. D. L. (2010). Effective communication about complex environmental issues: Perceived quality of information about carbon dioxide capture and storage (CCS) depends on stakeholder collaboration. *Journal of Environmental Psychology, 30*(4), 347-357. doi: 10.1016/j.jenvp.2010.06.001.

Thewys, T., & Kuppens, T. (2008). Economics of willow pyrolysis after phytoextraction. *Int J Phytoremediation, 10*(6), 561-583.

Thrän, D., Seidenberger, T., Zeddies, J., & Offermann, R. (2010). Global biomass potentials -- Resources, drivers and scenario results. *Energy for Sustainable Development, 14*(3), 200-205. doi: 10.1016/j.esd.2010.07.004.

Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L., …Somerville, C. (2009). Beneficial biofuels—the food, energy, and environment trilemma. *Science, 325*(5938), 270.

Tonini, D., & Astrup, T. (2012). LCA of biomass-based energy systems: A case study for Denmark. *Applied Energy, 99*(0), 234-246. doi: 10.1016/j.apenergy.2012.03.006.

Truelove, H. B. (2012). Energy source perceptions and policy support: Image associations, emotional evaluations, and cognitive beliefs. *Energy Policy, 45*, 478-489.

Tufvesson, L. M., Lantz, M., & Börjesson, P. (2013). Environmental performance of biogas produced from industrial residues including competition with animal feed – life-cycle calculations according to different methodologies and standards. *Journal of Cleaner Production, 53*(0), 214-223. doi: 10.1016/j.jclepro.2013.04.005.

Turcksin, L., Macharis, C., Lebeau, K., Boureima, F., Van Mierlo, J., Bram, S., …Pelkmans, L. (2011). A multi-actor multicriteria framework to assess the stakeholder support for different biofuel options: The case of Belgium. *Energy Policy, 39*(1), 200-214. doi: 10.1016/j.enpol.2010.09.033.

Ulrich, G. D. (1984). *A guide to Chemical Engineering Process Design and Economics*.

UN. (2005). UNECE Strategy for education for sustainable development *Economic and Social Council*: United Nations.

Upham, P., & Shackley, S. (2007). Local public opinion of a proposed 21.5 MW(e) biomass gasifier in Devon: Questionnaire survey results. *Biomass and Bioenergy, 31*(6), 433-441. doi: 10.1016/j.biombioe.2007.01.017.

Upham, P., Shackley, S., & Waterman, H. (2007). Public and stakeholder perceptions of 2030 bioenergy scenarios for the Yorkshire and Humber region. *Energy Policy, 35*(9), 4403-4412. doi: 10.1016/j.enpol.2007.03.002.

Upreti, B. R. (2004). Conflict over biomass energy development in the United Kingdom: some observations and lessons from England and Wales. *Energy Policy, 32*(6), 785-800. doi: 10.1016/S0301-4215(02)00342-7.

Upreti, B. R., & van der Horst, D. (2004). National renewable energy policy and local opposition in the UK: the failed development of a biomass electricity plant. *Biomass & Bioenergy, 26*(1), 61-69. doi: Doi 10.1016/S0961-9534(03)00099-0.

Urbaniec, K., Friedl, A., Huisingh, D., & Claassen, P. (2010). Hydrogen for a sustainable global economy. *Journal of Cleaner Production, 18, Supplement 1*(0), S1-S3. doi: 10.1016/j.jclepro.2010.05.010.

Uris, M., Linares, J. I., & Arenas, E. (2014). Techno-economic feasibility assessment of a biomass cogeneration plant based on an Organic Rankine Cycle. *Renewable Energy, 66*(0), 707-713. doi: 10.1016/j.renene.2014.01.022.

Valdez-Vazquez, I., Acevedo-Benítez, J. A., & Hernández-Santiago, C. (2010). Distribution and potential of bioenergy resources from agricultural activities in Mexico. *Renewable and Sustainable Energy Reviews, 14*(7), 2147-2153. doi: 10.1016/j.rser.2010.03.034.

Van Dael, M., Márquez, N., Reumerman, P., Pelkmans, L., Kuppens, T., & Van Passel, S. (2013). Development and techno-economic evaluation of a biorefinery based on biomass (waste) streams – case study in the Netherlands. *Biofuels, Bioproducts and Biorefining*, n/a-n/a. doi: 10.1002/bbb.1460.

Van Dael, M., Van Passel, S., Pelkmans, L., Guisson, R., Reumermann, P., Luzardo, N. M., . . . Broeze, J. (2013). A techno-economic evaluation of a biomass energy conversion park. *Applied Energy, 104*, 611-622.

Van Dael, M., Van Passel, S., Pelkmans, L., Guisson, R., Swinnen, G., & Schreurs, E. (2012). Determining Potential Locations for Biomass Valorization using a Macro Screening Approach. *Biomass and Bioenergy, 45*: 175-186.

van Dam, J., Faaij, A. P. C., Lewandowski, I., & Fischer, G. (2007). Biomass production potentials in Central and Eastern Europe under different scenarios. *Biomass and Bioenergy, 31*(6), 345-366. doi: 10.1016/j.biombioe.2006.10.001.

van den Hoogen, W. M. (2007). *From "bio-what?" to "bio-watt!": contextual influences on the formation of attitudes towards novel energy technologies.* Technische Universiteit Eindhoven. Retrieved from http://alexandria.tue.nl/extra2/200710723.pdf.

van den Pol-Dasselaar, A., Durksz, D., Klop, A., & Gosselink, J. M. J. (2012). Grasraffinage in de veehouderij. 23. Retrieved from http://edepot.wur.nl/206662.

van der Horst, D. (2007). NIMBY or not? Exploring the relevance of location and the politics of voiced opinions in renewable energy siting controversies. *Energy Policy, 35*(5), 2705-2714. doi: 10.1016/j.enpol.2006.12.012.

van der Zee, D. J., Achterkamp, M. C., & de Visser, B. J. (2004). Assessing the market opportunities of landfill mining. *Waste Management, 24*(8), 795-804. doi: 10.1016/j.wasman.2004.05.004.

Van Hoesen, J., & Letendre, S. (2010). Evaluating potential renewable energy resources in Poultney, Vermont: A GIS-based approach to supporting rural community energy planning. *Renewable Energy, 35*(9), 2114-2122. doi: 10.1016/j.renene.2010.01.018.

Van Huylenbroeck, G., & Damasco-Tagarino, D. (1998). Analysing crop choice of Philippine vegetable farmers with multicriteria analysis. *Journal of Multicriteria Decision Analysis, 7*(3), 160-168. doi: 10.1002/(sici)1099-1360(199805)7:3<160::aid-mcda186>3.0.co;2-I.

Van Passel, S., Dubois, M., Eyckmans, J., de Gheldere, S., Ang, F., Jones, P. T., & Van Acker, K. (2012). The Economics of Enhanced Landfill Mining: private and societal performance drivers. *Journal of Cleaner Production, 55*: 92-102.

Van Stappen, F., Brose, I., & Schenkel, Y. (2011). Direct and indirect land use changes issues in European sustainability initiatives: State-of-the-art, open issues and future developments. *Biomass and Bioenergy, 35*(12), 4824-4834. doi: 10.1016/j.biombioe.2011.07.015.

van Tilburg, X., Lensink, S., Londo, H., Cleijne, J., Pfeiffer, E., Mozaffarian, M., …Burgers, J. (2008). Technisch-economische parameters van duurzame energieopties in 2009-2010 (pp. 52). The Netherlands: KEMA.

Vandeweyer, H., Baert, R., Ryckebosch, E., Leenknegt, J., Drouillon, M., & Vervaeren, H. (2008). Biomethaan: opwerking van biogas tot aardgaskwaliteit. 176.

Vaneeckhaute, C., Meers, E., Michels, E., Buysse, J., & Tack, F. M. G. (2013). Ecological and economic benefits of the application of bio-based mineral fertilizers in modern agriculture. *Biomass and Bioenergy, 49*(0), 239-248. doi: 10.1016/j.biombioe.2012.12.036.

VCM (2004). Mestverwerking op het landbouwbedrijf: mogelijkheden en kostprijs. From http://www.vcm-mestverwerking.be/publicationfiles/N-IV-MESTVERWERKINGOPHETLANDBOUWBEDRIJF1.pdf.

Verbrugge, S., Casier, K., Van Ooteghem, J., & Lannoo, B. (2008, Sept. 28 2008-Oct. 2 2008). *Practical steps in techno-economic evaluation of network deployment planning part 1: methodology overview.* Paper presented at the The 13th International Telecommunications Network Strategy and Planning Symposium. Networks 2008.

Vereijken, P. H., & Hermans, C. M. L. (2010). A quick scan tool to assess the relative prospects of European regions for sustainable agriculture in a liberal market. *Land Use Policy, 27*(2), 440-448. doi: 10.1016/j.landusepol.2009.06.002.

Villela Filho, M., Araujo, C., Bonf, #225, , A., & Porto, W. (2011). Chemistry Based on Renewable Raw Materials: Perspectives for a Sugar Cane-Based Biorefinery. *Enzyme Research, 2011*. doi: 10.4061/2011/654596**.**

Vlaamse Overheid (2013). Bioeconomy in Flanders - The vision and strategy of the Government of Flanders for a sustainable and competitive bioeconomy in 2030. From http://www.vlaanderen.be/nl/publicaties/detail/bioeconomy-in-flanders.

Vlysidis, A., Binns, M., Webb, C., & Theodoropoulos, C. (2011). A techno-economic analysis of biodiesel biorefineries: Assessment of integrated designs for the co-production of fuels and chemicals. *Energy, 36*(8), 4671-4683. doi: 10.1016/j.energy.2011.04.046.

Voets, T., Kuppens, T., Cornelissen, T., & Thewys, T. (2011). Economics of electricity and heat production by gasification or flash pyrolysis of short rotation coppice in Flanders (Belgium). *Biomass and Bioenergy, 35*(5), 1912-1924. doi: 10.1016/j.biombioe.2011.01.034.

Voets, T., Neven, A., Thewys, T., & Kuppens, T. (2013). GIS-BASED location optimization of a biomass conversion plant on contaminated willow in the Campine region (Belgium). *Biomass and Bioenergy, 55*(0), 339-349. doi: 10.1016/j.biombioe.2013.02.037.

Vogtländer, J. G., Brezet, H. C., & Hendriks, C. F. (2001). Allocation in recycling systems. *The International Journal of Life Cycle Assessment, 6*(6), 344-355.

Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders. *Environmental Modelling & Software, 25*(11), 1268-1281. doi: 10.1016/j.envsoft.2010.03.007.

Voivontas, D., Assimacopoulos, D., & Koukios, E. G. (2001). Aessessment of biomass potential for power production: a GIS based method. *Biomass and Bioenergy, 20*(2), 101-112. doi: 10.1016/s0961-9534(00)00070-2.

Vose, D. (2000). *Risk analysis – a quantitative guide*. Chichester: John Wiley & Sons.

Walker, L., Charles, W., & Cord-Ruwisch, R. (2009). Comparison of static, in-vessel composting of MSW with thermophilic anaerobic digestion and combinations of the two processes. *Bioresource Technology, 100*(16), 3799-3807. doi: 10.1016/j.biortech.2009.02.015.

Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., & Zhao, J.-H. (2009). Review on multicriteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews, 13*(9), 2263-2278. doi: 10.1016/j.rser.2009.06.021.

Warman, P. R., Rodd, A. V., & Hicklenton, P. (2009). The effect of MSW compost and fertilizer on extractable soil elements and the growth of winter squash in Nova Scotia. *Agriculture, Ecosystems & Environment, 133*(1–2), 98-102. doi: 10.1016/j.agee.2009.05.010.

Warner, J. C., Cannon, A. S., & Dye, K. M. (2004). Green chemistry. *Environmental Impact Assessment Review, 24*(7–8), 775-799. doi: 10.1016/j.eiar.2004.06.006.

Weiland, P., Verstraete, W., & Van Haandel, A. (2009). Biomass Digestion to Methane in Agriculture: A Successful Pathway for the Energy Production and Waste Treatment Worldwide *Biofuels* (pp. 171-195): John Wiley & Sons, Ltd.

Werf, M. v. d. (2011). Formula structure and dataset for the anaerobic digestion profit calculator. In BioEnergyFarm (Ed.): Cornelissen consulting services BV.

Whittaker, C., McManus, M. C., & Hammond, G. P. (2011). Greenhouse gas reporting for biofuels: A comparison between the RED, RTFO and PAS2050 methodologies. *Energy Policy, 39*(10), 5950-5960. doi: 10.1016/j.enpol.2011.06.054.

Wille, D. (2009). Economische marktanalyse voor een duurzame verwerking van (deelstromen) van groen- en gft-afval met voorstel van beleidsaanbevelingen (pp. 128). Belgium: OVAM.

Wilson, G., & Wood, K. (2004). The influence of children on parental purchases during supermarket shopping. *International Journal of Consumer Studies, 28*(4), 329-336. doi: 10.1111/j.1470-6431.2004.00393.x.

Winston, W. L. (2003). Operations research - applications and algorithms. International Thomson Publishing.

Wright, W., & Reid, T. (2011). Green dreams or pipe dreams?: Media framing of the U.S. biofuels movement. *Biomass and Bioenergy, 35*(4), 1390-1399. doi: 10.1016/j.biombioe.2010.07.020.

Yan, J., & Lin, T. (2009). Biofuels in Asia. *Applied Energy, 86, Supplement 1*(0), S1-S10. doi: 10.1016/j.apenergy.2009.07.004.

Yin, J. (1999). Elite Opinion and Media Diffusion: Exploring Environmental Attitudes. *The Harvard International Journal of Press/Politics, 4*(3), 62-86. doi: 10.1177/1081180x99004003006.

Yoder, J., Galinato, S., Granatstein, D., & Garcia-Pérez, M. (2011). Economic tradeoff between biochar and bio-oil production via pyrolysis. *Biomass and Bioenergy, 35*(5), 1851-1862. doi: 10.1016/j.biombioe.2011.01.026.

Yohanis, Y. G. (2012). Domestic energy use and householders' energy behaviour. *Energy Policy, 41*(0), 654-665. doi: 10.1016/j.enpol.2011.11.028.

Zhang, Y., Dubé, M. A., McLean, D. D., & Kates, M. (2003). Biodiesel production from waste cooking oil: 2. Economic assessment and sensitivity analysis. *Bioresource Technology, 90*(3), 229-240. doi: 10.1016/S0960-8524(03)00150-0.

Zianis, D., Muukkonen, P., Mäkipää, R., & Mencuccini, M. (2005). Biomass and stem volume equa¬tions for tree species in Europe. *Silva Fennica Monographs 4*, 63.

Zografakis, N., Menegaki, A. N., & Tsagarakis, K. P. (2008). Effective education for energy efficiency. *Energy Policy, 36*(8), 3226-3232. doi: 10.1016/j.enpol.2008.04.021.

Zopounidis, C. and P. M. Pardalos (2010). Handbook of Multicriteria Analysis. Berlin Heidelberg, Springer-Verlag.

Zubaryeva, A., Zaccarelli, N., Del Giudice, C., & Zurlini, G. (2012). Spatially explicit assessment of local biomass availability for distributed biogas production via anaerobic co-digestion – Mediterranean case study. *Renewable Energy, 39*(1), 261-270. doi: 10.1016/j.renene.2011.08.021.

Zwick, W. R., & Velicer, W. F. (1986). Comparison of five rules for determining the number of components to retain. *Psychological Bulletin, 99*, 432-442.

Zyadin, A., Puhakka, A., Ahponen, P., Cronberg, T., & Pelkonen, P. (2012). School students' knowledge, perceptions, and attitudes toward renewable energy in Jordan. *Renewable Energy, 45*, 78-85.

APPENDICES

Appendix 1. Calculation method consistency index

To calculate the consistency index (CI), the following three steps have to be performed.

Step 1: Compute A$\mathbf{w}^{T}$, which is the pairwise comparison matrix A times the column vector $\mathbf{w}^{T}$ with the decision maker's weights.

Step 2: Compute $\frac{1}{n}\sum_{i\ 1}^{i\ n}\frac{ith\ entry\ in\ Aw^{T}}{ith\ entry\ in\ \mathbf{w}^{T}}$ with n the number of objectives (*i.e.* criteria)

Step 3: Compute $CI = \frac{(Step\ 2\ result)-n}{n-1}$

Appendix 2. Investment costs, expenditures and revenues for the case Breda

OMSW digester (mono-dimensional)

Investment costs	**€ 34,113,035**
UASB reactor	€ 12,943,638
CHP installation	€ 646,296
Composting installation	€ 16,537,855
Heat network	€ 1,030,000
Site preparation	€ 2,955,246
Operational costs	**€ 3,507,820**
Repair cost	€ 682,261
Insurance cost	€ 341,130
Electricity cost site	€ 110,623
Maintenance cost UASB reactor	€ 388,309
Analysis cost input digester	€ 106,880
Personnel cost digester	€ 72,000
Operational & maintenance cost CHP	€ 120,792
Maintenance cost composting	€ 618,224
Operational cost composting	€ 556,402
Red diesel cost	€ 16,938
Personnel cost composting	€ 464,261
Maintenance cost heat network	€ 30,000
Revenues	**€ 9,223,157**
Avoided cost electricity	€ 495,790
Sale green electricity	€ -
Sale heat	€ 29,470
Municipal organic waste	€ 3,840,000
Forfait municipal organic waste	€ 4,590,000
Compost	€ 114,990
SDE+ CHP	€ 152,908

Co-digestion (mono-dimensional)

Investment costs	**€ 10,258,137**
Hygienisation	€ 46,014
Dry digester	€ 5,405,923
CHP installation	€ 553,417
Separator	€ 29,682
UFRO separator	€ 2,956,216
Dryer 1	€ 43,752
Dryer 2	€ 87,840
Dryer 3	€ 61,488
Wood boiler	€ 152,488
Site preparation	€ 921,317
Operational costs	**€ 921,569**
Repair cost	€ 205,163
Insurance cost	€ 102,581
Electricity cost site	€ -
Maintenance cost dry digester	€ 86,495
Analysis cost input dry digester	€ 40,080
Personnel cost dry digester	€ 72,000
Operational & maintenance cost CHP	€ 93,641
Maintenance cost separator	€ 890
Personnel cost separator	€ 18,000
Maintenance cost UFRO separator	€ 88,686
Personnel cost UFRO separator	€ 45,000
Maintenance cost dryer 1	€ 2,552
Personnel cost dryer 1	€ 22,970
Maintenance cost dryer 2	€ 8,784
Personnel cost dryer 2	€ 46,116
Maintenance cost dryer 3	€ 8,198
Personnel cost dryer 3	€ 32,281
Maintenance cost wood boiler	€ 4,575
Wood cost	€ 40,435
Ash disposal cost	€ 3,121
Revenues	**€ 756,936**
Avoided cost electricity	€ 224,079

Sale green electricity	€ 51,960
Sale heat	€ -
Manure	€ 400,000
Co-substrates	€ -40,000
Dry manure	€ -37,918
Retentate UF	€ -46,848
Retentate RO	€ 2,460
SDE+ CHP	€ 179,964
SDE+ wood boiler	€ 23,239

Energy Conversion Park (multi-dimensional)

Investment costs	**€ 43,008,788**
Hygienisation	€ 46,014
UASB reactor	€ 12,943,638
Composting installation	€ 16,537,855
Dry digester	€ 5,405,923
CHP installation	€ 992,001
Separator	€ 29,682
UFRO separator	€ 2,956,216
Dryer 1	€ 43,752
Dryer 2	€ 87,840
Dryer 3	€ 61,488
Wood boiler	€ 58,033
Site preparation	€ 3,846,347
Operational costs	**€ 4,194,399**
Repair cost	€ 860,176
Insurance cost	€ 430,088
Electricity cost site	€ -
Maintenance cost UASB reactor	€ 388,309
Analysis cost input digester	€ 106,880
Personnel cost digester	€ 72,000
Operational & maintenance cost CHP	€ 195,089
Maintenance cost composting	€ 618,224
Operational cost composting	€ 556,402
Red diesel cost	€ 16,938
Personnel cost composting	€ 464,261

Maintenance cost dry digester	€ 86,495
Analysis cost input dry digester	€ 40,080
Personnel cost dry digester	€ 72,000
Maintenance cost separator	€ 890
Personnel cost separator	€ 18,000
Maintenance cost UFRO separator	€ 88,686
Personnel cost UFRO separator	€ 45,000
Maintenance cost dryer 1	€ 2,552
Personnel cost dryer 1	€ 22,970
Maintenance cost dryer 2	€ 8,784
Personnel cost dryer 2	€ 46,116
Maintenance cost dryer 3	€ 8,198
Personnel cost dryer 3	€ 32,281
Maintenance cost wood boiler	€ 1,741
Wood cost	€ 11,361
Ash disposal cost	€ 877
Revenues	**€ 10,087,256**
Avoided cost electricity	€ 830,492
Sale green electricity	€ 12,282
Sale heat	€ -
Municipal organic waste	€ 3,840,000
Forfait municipal organic waste	€ 4,590,000
Compost	€ 114,990
Manure	€ 400,000
Co-substrates	€ -40,000
Dry manure	€ -37,918
Retentate UF	€ -46,848
Retentate RO	€ 2,460
SDE+ CHP	€ 421,799

Appendix 3. Investment costs, expenditures and revenues for the case Moerdijk

Digestion

Investment costs	**€ 19,307,783**
Dry digester	€ 12,967,068
Upgrading	€ 1,616,685
LBM	€ 616,593
Dryer	€ 2,352,184
Site preparation	€ 1,755,253
Operational costs	**€ 3,315,594**
Repair cost	€ 386,156
Insurance cost	€ 193,078
Electricity cost site	€ 501,707
Heat cost site	€ 968,755
Maintenance cost dry digester	€ 207,473
Analysis cost input dry digester	€ 125,173
Personnel cost dry digester	€ 32,000
Maintenance cost upgrading	€ 154,148
Compression cost upgrading	€ 172,949
Quality control upgrading	€ 16,167
Maintenance cost LBM	€ 96,447
Maintenance cost dryer	€ 108,712
Personnel cost dryer	€ 352,828
Revenues	**€ 3,541,838**
Avoided cost electricity	€ -
Avoided cost heat	€ 91,350
Sale green electricity	€ -
Sale heat	€ -
Municipal organic waste	€ 631,960
Manure	€ 89,017
Residue juice	€ 405,698
Glycerin	€ -90,000
Dry digestate	€ -355,805
CO_2	€ 217,561

LBM	€ 1,293,670
Biotickets	€ 1,258,388

Grass refinery

Investment costs	**€ 2,653,184**
Grass refinery	€ 568,966
Dryer	€ 1,843,019
Site preparation	€ 241,199
Operational costs	**€ 960,978**
Repair cost	€ 53,064
Insurance cost	€ 26,532
Electricity cost site	€ 24,558
Heat cost site	€ 543,900
Maintenance cost dryer	€ 64,028
Maintenance cost grass refinery	€ 56,897
Personnel cost grass refinery	€ 192,000
Revenues	**€ 264,515**
Avoided cost electricity	€ -
Avoided cost heat	€ -
Sale green electricity	€ -
Sale heat	€ -
Nature grass	€ -
Protein	€ 670,212
Residue juice	€ 405,698

Esterification

Investment costs	**€ 4,874,934**
Esterification	€ 4,431,758
Site preparation	€ 443,176
Operational costs	**€ 6,754,392**
Repair cost	€ 97,499
Insurance cost	€ 48,749
Electricity cost site	€ 46,608

Heat cost site	€ 170,896
Operational cost esterification	€ 443,176
Personnel cost esterification	€ 384,000
Residue fats	€ 4,800,000
Methanol	€ 571,200
H_2SO_4	€ 191,552
Water	€ 712
Revenues	**€ 8,546,596**
Avoided cost electricity	€ -
Avoided cost heat	€ -
Sale green electricity	€ -
Sale heat	€ -
Biodiesel	€ 5,359,920
Disposal cost water	€ -95,040
Glycerin	€ 90,000
Biotickets	€ 3,191,716

Pyrolysis

Investment costs	**€ 20,959,231**
Dryer	€ 1,750,000
Sizing	€ 434,200
Pyrolysis	€ 16,869,646
Site preparation	€ 1,905,385
Operational costs	**€ 5,204,975**
Repair cost	€ 419,185
Insurance cost	€ 209,592
Electricity cost site	€ -
Heat cost site	€ -
Maintenance cost dryer	€ 13,158
Personnel cost dryer	€ 262,500
Wood	€ 2,750,000
Maintenance cost sizing	€ 13,026
Operational & maintenance pyrolysis	€ 843,482
Personnel cost pyrolysis	€ 442,383
Disposal cost ash biochar	€ 109,158
Water	€ 142,491

Revenues	**€ 9,109,354**
Avoided cost electricity	€ 822,839
Avoided cost heat	€ 1,010,513
Sale green electricity	€ 371,496
Sale heat	€ -
Dry digestate	€ 355,805
Pyrolysis oil	€ 6,548,701

ECP

Investment costs	**€ 47,795,132**
Grass refinery	€ 568,966
Dryer 1	€ 1,843,019
Dryer 2	€ 1,750,000
Dryer 3	€ 2,352,184
Sizing	€ 434,200
Pyrolysis	€ 16,869,646
Esterification	€ 4,431,758
Dry digester	€ 12,967,068
Upgrading	€ 1,616,685
LBM	€ 616,593
Site preparation	€ 4,345,012
Operational costs	**€ 14,417,336**
Repair cost	€ 955,903
Insurance cost	€ 477,951
Electricity cost site	€ -
Heat cost site	€ 1,053,150
Maintenance cost grass refinery	€ 56,897
Personnel cost grass refinery	€ 192,000
Maintenance cost dryer 1	€ 64,028
Maintenance cost dryer 2	€ 13,158
Wood	€ 2,750,000
Maintenance cost dryer 3	€ 108,712
Maintenance cost sizing	€ 13,026
Operational & maintenance pyrolysis	€ 843,482
Personnel cost pyrolysis	€ 442,383

Disposal cost ash biochar	€ 109,158
Water pyrolysis	€ 142,491
Operational cost esterification	€ 443,176
Personnel cost esterification	€ 384,000
Residue fats	€ 4,800,000
Methanol	€ 571,200
H_2SO_4	€ 191,552
Water	€ 712
Maintenance cost dry digester	€ 207,473
Analysis cost input dry digester	€ 125,173
Personnel cost dry digester	€ 32,000
Maintenance cost upgrading	€ 154,148
Compression cost upgrading	€ 172,949
Quality control upgrading	€ 16,167
Maintenance cost LBM	€ 96,447
Revenues	**€ 22,743,018**
Avoided cost electricity	€ 1,395,712
Avoided cost heat	€ 2,096,142
Sale green electricity	€ 85,060
Sale heat	€ -
Organic municipal solid waste	€ 631,960
Manure	€ 89,017
Protein	€ 670,212
Pyrolysis oil	€ 6,548,701
Biodiesel	€ 5,359,920
Disposal cost water	€ -95,040
CO_2	€ 217,561
LBM	€ 1,293,670
Biotickets	€ 4,450,104

Appendix 4. Questionnaire

Kennisvragen	
1.1 Welke van volgende energiebronnen zijn hernieuwbaar? (meerdere antwoorden mogelijk)	□ Aardgas □ Schaliegas □ Wind □ Olie □ Biomassa □ Zon □ Waterkracht □ Steenkool □ Geothermie □ Kernenergie
1.2 Wat zijn volgens jou voordelen van hernieuwbare energie ten opzichte van fossiele alternatieven? (meerdere antwoorden mogelijk)	□ Afname van de afhankelijkheid van fossiele grondstoffen. □ Daling in broeikasgasemissies. □ Stimuleren van lokale economie. □ Goedkopere energie. □ Ik weet het niet
1.3 Wat is volgens jou het huidige aandeel van hernieuwbare energie in Vlaanderen?	□ <5% □ 5-10% □ 10-15% □ 15-20% □ > 20% □ Ik weet het niet
1.4 Wat is volgens jou het huidige aandeel van bio-energie in de totale hoeveelheid hernieuwbare energie in Vlaanderen?	□ <20% □ 21-40% □ 41-60% □ 61-80% □ 81-100% □ Ik weet het niet
1.5 Had je al gehoord van bio-energie voor deze enquête?	□ Ja □ Nee (ga verder naar vraag 1.8)
1.6 Via welk kanaal had je al gehoord van bio-energie voor deze enquête? (meerdere antwoorden mogelijk)	□ School □ Ouders □ Krant □ TV □ Radio □ Tijdschrift □ Internet □ Familie/vrienden □ Andere: …

1.7 Van welke vormen van bio-energie had je al gehoord? (meerdere antwoorden mogelijk)	□ Warmte op basis van hout □ Elektriciteit op basis van hout □ Biogas □ Transportbrandstof (bv. Biodiesel, Bio-ethanol) □ Andere: …
1.8 Bio-energie is energie geproduceerd van de biologische fractie van producten, afvalstoffen en residuen van onder andere de landbouw en bosbouw.	□ Akkoord □ Niet akkoord □ Ik weet het niet
1.9 Biodiesel wordt gemaakt van olie afkomstig van planten.	□ Akkoord □ Niet akkoord □ Ik weet het niet
1.10 Hoe schat je jouw eigen kennis van bio-energie in vergeleken met een gemiddelde leeftijdgenoot?	□ Zeer laag □ Laag □ Eerder laag □ gemiddeld □ Eerder hoog □ Hoog □ Zeer hoog
1.11 Heb je kennis van een biomassa-installatie bij jou in de buurt?	□ Ja □ Nee Indien ja, wat is ongeveer de afstand tot je woonplaats? □ <2 km □ 2-5 km □ 5-10 km □ >10 km □ Weet ik niet

Voor het invullen van de volgende vragen geven we eerst een definitie van biomassa en bio-energie.

Biomassa is het biologische gedeelte van producten, afvalstoffen en resten van de landbouw, de bosbouw en aanverwante bedrijfstakken. Maar ook het biologisch afbreekbare gedeelte van industrieel en huishoudelijk afval. Voorbeelden van biomassa zijn: hout, GFT, mest, maaisel, en stro.

Bio-energie is energie geproduceerd uit biomassa.

Perceptie vragen								
2.1	Helemaal niet akkoord	Niet akkoord	Eerder niet akkoord	Noch akkoord, Noch niet akkoord	Eerder akkoord	Akkoord	Helemaal akkoord	Ik weet het niet
Een toename in het gebruik van bio-energie kan helpen het broeikasgas effect te verminderen. (1)	O	O	O	O	O	O	O	O
Bio-energie kan het gebruik van fossiele brandstoffen in de toekomst vervangen. (2)	O	O	O	O	O	O	O	O
Bio-energie zal in de toekomst de belangrijkste bron zijn voor energie in België. (3)	O	O	O	O	O	O	O	O
Een stijging in bio-energie kan leiden tot een daling in voedselproductie. (4)	O	O	O	O	O	O	O	O
Hout zal in de toekomst een van de belangrijkste bronnen zijn voor bio-energie in België. (5)	O	O	O	O	O	O	O	O

2.2	Helemaal niet akkoord	Niet akkoord	Eerder niet akkoord	Noch akkoord, Noch niet akkoord	Eerder akkoord	Akkoord	Helemaal akkoord	Ik weet het niet
Productie van energie uit hout is milieuvriendelijk. (1)	O	O	O	O	O	O	O	O
Het kappen van bomen voor energieproductie is verantwoord wanneer dezelfde hoeveelheid bomen opnieuw wordt aangeplant. (2)	O	O	O	O	O	O	O	O
Productie van energie uit biomassa-afvalstromen zoals mest, GFT of maaisel is milieuvriendelijk. (3)	O	O	O	O	O	O	O	O
Afvalstromen zoals mest, GFT of maaisel zullen in de toekomst een van de belangrijkste bronnen zijn voor energie in België. (4)	O	O	O	O	O	O	O	O
De overheid zou onderzoek en ontwikkeling van bio-energie moeten ondersteunen. (5)	O	O	O	O	O	O	O	O

Attitude vragen								
3.1	Helemaal niet akkoord	Niet akkoord	Eerder niet akkoord	Noch akkoord, Noch niet akkoord	Eerder akkoord	Akkoord	Helemaal akkoord	Ik weet het niet
Ik zou in de toekomst willen rijden met een biobrandstof (bv biomethaan of biodiesel). (1)	O	O	O	O	O	O	O	O
Ik zou graag een bio-energie installatie in mijn regio gaan bezoeken. (2)	O	O	O	O	O	O	O	O
Ik zou graag meer leren over bio-energie in de toekomst. (3)	O	O	O	O	O	O	O	O
Ik zou graag met mijn docenten discussiëren over bio-energie. (4)	O	O	O	O	O	O	O	O
Ik zou graag met mijn ouders discussiëren over bio-energie. (5)	O	O	O	O	O	O	O	O
Ik zou graag met mijn klasgenoten discussiëren over bio-energie. (6)	O	O	O	O	O	O	O	O
Ik ben milieubewust. (7)	O	O	O	O	O	O	O	O

3.2	Helemaal niet akkoord	Niet akkoord	Eerder niet akkoord	Noch akkoord, Noch niet akkoord	Eerder akkoord	Akkoord	Helemaal akkoord	Ik weet het niet
Ik zou in de toekomst graag gebruik maken van bio-energie in mijn huis. (1)	O	O	O	O	O	O	O	O
Ik zou bio-energie kopen. (2)	O	O	O	O	O	O	O	O
Ik zou bio-energie aankopen voor mijn energievoorziening, zelfs als dat meer zou kosten. (3)	O	O	O	O	O	O	O	O

3.3 Hoeveel hoger mag de prijs voor bio-energie liggen opdat je dit nog zou kopen? (slechts één antwoord mogelijk)	□ <1% □ 1-5% □ 5-10% □ 10-15% □ >15% □ De prijs mag niet hoger liggen □ Ik zou dit sowieso niet kopen.
3.4 Hoe verwarm je graag je huis in de toekomst? (slechts één antwoord mogelijk)	□ Hout □ Biogas □ Gas □ Elektriciteit op basis van fossiele energie □ Elektriciteit op basis van wind □ Zon □ Verbranding van kolen □ Warmtepomp □ Andere:… □ Ik weet het niet

3.5	Helemaal niet akkoord	Niet akkoord	Eerder niet akkoord	Noch akkoord, Noch niet akkoord	Eerder akkoord	Akkoord	Helemaal akkoord	Ik weet het niet
Mijn mening over het gebruik van biomassa als bron voor energie zal waarschijnlijk nog veranderen. (1)	O	O	O	O	O	O	O	O
Het gebruik van biomassa als bron voor de opwekking van energie, is een belangrijk onderwerp. (3)	O	O	O	O	O	O	O	O
Het gebruik van biomassa als bron voor de opwekking van energie, is een onderwerp waarbij je je betrokken voelt. (4)	O	O	O	O	O	O	O	O

3.6 In welke mate ben je akkoord met de volgende stelling: Ik voel een strijd tussen de voordelen en nadelen van het gebruik van biomassa als bron voor de opwekking van energie. Soms zie ik eerder de positieve aspecten, soms zie ik eerder de negatieve aspecten.	□ Helemaal niet akkoord □ Niet akkoord □ Eerder niet akkoord □ Noch akkoord, Noch niet akkoord □ Eerder akkoord □ Akkoord □ Helemaal akkoord
3.7 Denk alleen aan de positieve eigenschappen van het gebruik van biomassa als bron voor de opwekking van energie en negeer de negatieve, hoe positief vind je deze positieve eigenschappen?	□ Helemaal niet positief □ Een beetje positief □ Neutraal □ Behoorlijk positief □ Heel erg positief

3.8 Denk alleen aan de negatieve eigenschappen van het gebruik van biomassa als bron voor de opwekking van energie en negeer de positieve, hoe negatief vind je deze negatieve eigenschappen?	□ Helemaal niet negatief □ Een beetje negatief □ Neutraal □ Behoorlijk negatief □ Heel erg negatief
3.9 In hoeverre ben je akkoord met de volgende stelling: Voor mij slaat de balans tussen de voor- en nadelen van biomassa als bron voor de opwekking van energie duidelijk uit naar één kant.	□ Helemaal niet akkoord □ Niet akkoord □ Eerder niet akkoord □ Noch akkoord, Noch niet akkoord □ Eerder akkoord □ Akkoord □ Helemaal akkoord

Algemene vragen	
4.1 Geslacht	□ Man □ Vrouw
4.2 Wat is jouw geboortejaar?	….
4.3 Postcode woonplaats	….
4.4 Straatnaam woonplaats (Dit laat ons toe na te gaan of u in de buurt van een biomassa-installatie woont)	…
4.5 Wat is je huidige studierichting?	…
4.6 Aan welke school/universiteit volg je les?	…
4.7 Wat is het hoogst behaalde diploma van je vader?	□ Lager onderwijs □ Secundair onderwijs □ Hoger onderwijs (niet-universitair) □ Universitair onderwijs □ Ik weet het niet
4.8 Wat is het hoogst behaalde diploma van je moeder?	□ Lager onderwijs □ Secundair onderwijs □ Hoger onderwijs (niet-universitair) □ Universitair onderwijs □ Ik weet het niet
4.9 Ben je lid van een milieu- of natuurvereniging?	□ Ja □ Nee

Opmerkingen	
Indien je nog opmerkingen hebt met betrekking tot de vragenlijst of het onderwerp van de vragenlijst, kan je die hier kwijt.	

Appendix 5. Knowledge questions and scoring

Question	score
1. Which of the energy sources below are renewable according to you?	
☐ Natural gas	
☐ Oil	
☐ **Bioenergy**	+ 0.2
☐ **Geothermal energy**	+ 0.2
☐ Nuclear energy	
☐ Coal	
☐ **Water energy**	+ 0.2
☐ **Wind energy**	+ 0.2
☐ **Solar energy**	+ 0.2
2. What is the share of renewable energy in the total primary energy usage in Belgium according to you?	
☐ **0% - 10%**	+ 1
☐ 11% - 20%	
☐ 21% - 30%	
☐ 31% - 40%	
☐ 41% - 50%	
☐ More than 50%	
☐ I don't know	
3. What is the share of bioenergy in the total renewable energy production in Flanders according to you?	
☐ 0% - 20%	
☐ 21% - 40%	
☐ **41% - 60%**	+ 1
☐ 61% - 80%	
☐ 81% - 100%	
☐ I don't know	
4. Bioenergy is the energy produced from the biological fraction of products, waste and residues of e.g. agriculture or forestry.	
☐ **Agree**	+ 1
☐ Disagree	
☐ I don't know	
5. Biodiesel is derived from oil of plants.	
☐ **Agree**	+ 1
☐ Disagree	
☐ I don't know	
Total	**= 5**

ACADEMIC BIBLIOGRAPHY

Journal Papers

Kuppens, T., Van Dael, M., Vanreppelen, K., Thewys, T., Yperman, J., Carleer, R., Schreurs, S., and Van Passel, S. (2014) Techno-economic assessment of fast pyrolysis for the valorization of short rotation coppice cultivated for phytoextraction. Journal of Cleaner Production doi: 10.1016/j.jclepro.2014.07.023.

Maes, D., Van Dael, M., Vanheusden, B., Goovaerts, L., Reumerman, P., Márquez Luzardo, N., and Van Passel, S. (2014) Assessment of the RED sustainability guidelines: the case of biorefineries. Journal of Cleaner Production doi: 10.1016/j.jclepro.2014.04.051.

Van Dael, M., Márquez, N., Reumerman, P., Pelkmans, L., Kuppens, T., and Van Passel, S. (2014) Development and techno-economic evaluation of a biorefinery based on biomass (waste) streams – case study in the Netherlands. *Biofuels, Bioprod. Bioref. 8, p. 635-644,* doi: 10.1002/bbb.1460.

Guisson, R. and Van Dael, M. (2013) Energy Conversion Park – A concept for the efficient use of regionally available biomass residue streams. Waste Management 33(8), p. 1689-1690.

Van Slycken, S., Witters, N., Meers, E., Peene, A., Michels, E. Adriaensens, K., Ruttens, A., Vangronsveld, J., Du Laing, G., Wierinck, I., Van Dael, M., Van Passel, S., and Tack, F. (2013) Safe use of metal-contaminated agricultural land by cultivation of energy maize (Zea mays). In: Environmental Pollution, 178, p. 375-380.

Van Dael, M., Van Passel, S., Pelkmans, L., Guisson, R., Reumerman, P., Marquez-Luzardo, N., Witters, N., and Broeze, J. (2013) A techno-economic evaluation of a biomass energy conversion park. Applied Energy 104(0), p. 611-622.

Van Dael, M., Van Passel, S., Pelkmans, L., Guisson, R., Swinnen, G., and Schreurs, E. (2012) Determining potential locations for biomass valorization using a macro screening approach. Biomass and Bioenergy 45(0), p. 175-186.

Journal papers submitted

Van Dael, M., Van Passel, S., Leroi-Werelds, S., and Swinnen, G. Biomass hot or not? Social acceptance of bioenergy in Belgium. Submitted.

Njakou Djomo, S., Witters, N., Van Dael, M., and Ceulemans, R. Energy and greenhouse gas performances of fixed and fluidized bed cogeneration technologies for bioheat and biopower production in Belgium. Submitted.

Vangansbeke, P., Osselaere, J., Van Dael, M., De Frenne, P., Gruwez, R., Pelkmans, L., Gorissen, L., and Verheyen, K. Sustainability analysis of logging operations in pine stands with additional harvest of woody biomass. Submitted.

International conferences

Kuppens, T., Van Dael, M., Vanreppelen, K., Yperman, J., Carleer, R., Elen, H., and Van Passel, S. (2014) Techno-economic assessment of different conversion pathways for pyrolysis char from pig manure. In: 22nd European Biomass Conference & Exhibition, Hamburg – Germany, 23-26 June 2014.

Billig, E., Devriendt, N., Thrän, D., Persson, T., Kranzl, L., Baldwin, J., Ponitka, J., Seiffert, M., Svensson, M., Matzenberger, J., Pelkmans, L., and Van Dael, M. (2014) Market deployment of biomethane in IEA member countries – focus on stakeholder questionnaire. In: 22nd European Biomass Conference & Exhibition, Hamburg – Germany, 23-26 June 2014.

Kuppens, T., Van Dael, M., Vanreppelen, K., Carleer, R., Yperman, J., Schreurs, S., Van Passel, S. (2014) Techno-economic assessment of pyrolysis char production and application – A review. In: Ranzi, Eliseo; Kohse-Hölinghaus, Katharina (Ed.). Chemical Engineering Transactions, p. 67-72. International Conference on Biomass (iconBM), Florence – Italy, 4-7 May 2014.

Pelkmans, L., Devriendt, N., Guisson, R., Cornelis, E., Goovaerts, L., Van Dael, M., Van Passel, S., and De Witte, J. (2014) Exploring integrated concepts for energy production from green waste. In: 4th Central European Biomass Conference, Graz – Austria, 15-18 January 2014.

Kuppens, T., Van Dael, M., Vanreppelen, K., Carleer, R., Yperman, J., and Van Passel, S. (2013) Techno-economic assessment of pyrolysis char production from pig manure. In: ManuREsource 2013 – International conference on manure management and valorization, Bruges – Belgium, 5-6 December 2013.

Maes, D., Goovaerts, L., Van Dael, M., Reumerman, P., Márquez, N., and Van Passel, S. (2013) Review of the RED sustainability guidelines when applied to multiple combined pathways of renewable energy. In: 8th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES 2013), Dubrovnik – Croatia, 22-27 September 2013.

Venselaar, J., Márquez, N., Reumerman, P., Van Dael, M., Broeze, J., and Pelkmans, L. (2013) Integrated processing of biomass resources to optimize economics and sustainability. In: 9th European Congress of Chemical Engineering, Den Haag - Nederland, 21-25 April 2013.

Guisson, R., Devriendt, N., Pelkmans, L., Van Dael, M., Annevelink, B., Broeze, J., Coppoolse, K., Márquez, N., Reumerman, P., Venselaar, J., Van Passel, S. (2013) How to Organize Initiatives for a Resource Efficient Use of Locally Available Biomass Waste and Residue Streams. In: 21st European Biomass Conference & Exhibition, Kopenhagen - Denemarken, 3-7 juni 2013.

Van Dael, M., Marquez Luzardo, N., Reumerman, P., Pelkmans, L., and Van Passel, S. (2013) Development and techno-economic evaluation of a biorefinery based on biomass (waste) streams. In: II Iberoamerican Congress on Biorefineries, Jaén, Spain, 10-12 april 2013.

Guisson, R., Van Dael, M., Van Passel, S., and Pelkmans, L. (2012) A bioenergy conversion park in the province of Limburg (Belgium) - an economic viability check of a biomass utilization concept for bioenergy. In: 20th European Biomass Conference & Exhibition, Milano, Italy, 18-22 June 2012, p. 2166-2171.

Maes, D., Van Dael, M., and Van Passel, S. (2012) The emergence of optimal configurations of biomass transformation as a direct result of conflicting subsidy regimes. In: Innovation for Sustainable Production, Brugge - Belgium, 6-9 May 2012.

Pelkmans, L., Devriendt, N., Cornelis, E., Guisson, R., Marquez-Luzardo, N., Venselaar, J., Broeze, J., Van Dael, M., Van Passel, S., Vollaard, P., Reumerman, P., and Coppoolse, K. (2012) Valorisation of biomass waste residues in energy conversion parks. In: 4th International Conference on Engineering for Waste and Biomass Valorisation, Porto - Portugal, 10-13 September 2012.

Van Dael, M., Broeze, J., Pelkmans, L., Devriendt, N., Pieper, H., Guisson, R., Cornelis, E., Venselaar, J., Marquez-Luzardo, N., Vollaard, P., Reumerman, P., Coppoolse, K., ten Berge, H., and Van Passel, S. (2012) A techno-economic evaluation of an energy conversion park. In: 8th International Conference on Renewable Resources and Biorefineries, France, Toulouse, 4-6 June 2012.

Guisson, R., Pelkmans, L., Devriendt, N., Marquez-Luzardo, N., Broeze, J., Van Dael, M., Van Passel, S., and Reumerman, P. (2012) Energy conversion parks - a concept case study for the efficient use of locally available biomass streams. In: 4th International Symposium on Energy from Biomass and Waste, Venice - Italy, 12-15 November 2012.

Van Dael, M., Witters, N., Guisson, R., and Van Passel, S. (2012) Long-term phytoremediation using fodder maize: an integrated approach leads to economic synergies. In: 9th International Phytotechnology Society (IPS) conference, Hasselt, Belgium, 11-14 September 2012.

Pelkmans, L., Devriendt, N., Guisson, R., Pieper, H., Marquez-Luzardo, N., Venselaar, J., Broeze, J., Van Dael, M., Van Passel, S., Vollaard, P., Reumerman, P., and Coppoolse, K. (2012) Valorisation of biomass waste streams in local energy conversion parks. *In: ORBIT2012, Rennes, France, 12-15 June 2012.*

Van Dael, M., Guisson, R., Pelkmans, L., and Van Passel, S. (2011) A biomass energy conversion park for optimal exploitation of regionally available biomass resources. In: International Conference Forests 2011, Leuven, Belgium, November 23-24, 2011.

Pelkmans, L., Devriendt, N., Cornelis, E., Guisson, R., Venselaar, J., Marquez Luzardo, N., Broeze, J., Van Passel, S., Van Dael, M., Vollaard, P., Reumerman, P., and Coppoolse, K. (2011) Energy conversion parks for the efficient use of locally available biomass streams. In: Nordic Bioenergy 2011 Conference, Jyväskylä, Finland, 6-7 September 2011.

Other

Maes, D., Van Dael, M., Vanheusden, B., Goovaerts, L., Reumerman, P., Márquez Luzardo, N., and Van Passel, S. (2014) Toepassen van de RED duurzaamheidsrichtlijnen voor bioraffinage. In: Nieuwsbrief Milieu & Economie.

Van Dael, M., Kuppens, T., Lizin, S., Van Passel, S. Techno-economic assessment of ultrasonic production of biofuels In: Zhen Fang, R. L. Smith, Jr., X. Qi (Editors), Production of Biofuels and Chemicals: Ultrasound, Springer Book Series - Biofuels and Biorefineries 4. DOI 10.1007/978-94-017-9624-8_12.

Van Dael, M., Van Passel, S., Pelkmans, L., Guisson, R., Reumerman, P., Marquez Luzardo, N., Witters, N., and Broeze, J. (2013) Techno-economische evaluatie van een biomassa-energieconversiepark. In: Nieuwsbrief Milieu & Economie, p. 1-4.

Devriendt, N., Van Dael, M., Pelkmans, L., and Cornelis, E. (2013) ECP Beerse/Merksplas: Organisatie.

Van Dael, M., Devriendt, N., and Van Passel, S. (2013) Economisch rapport ECP-case Beerse-Merksplas.

Guisson, R., and Van Dael, M. (2013) Eindrapport ECP-case Belgisch Limburg.

Cornelis, E., Devriendt, N., Van Dael, M., and Pelkmans, L. (2013) ECP Beerse/Merksplas: Biomassa Inventaris.

Gybels, R., Meers, E., Devacht, C., Annaert, W., Ryckaert, B., Verbeke, W., Schoutteten, H., Janssens, L., Van Gijzeghem, F., De Vocht, A., Delief, A., Witters, N., Van Dael, M., Wijgaerts, A., Vangronsveld, J., Vandaele, E., and Vandenbroek, K. (2012) Graskracht eindrapport.