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Multi-criteria comparative assessment of viable feedstocks for bioethanol production in Belgium

The case of wheat, sugar beet, miscanthus, and forest residue

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Abstract

The purpose of this master thesis is to conduct a multi-criteria decision analysis (MCDA) to determine the most sustainable scenario for bioethanol production in Belgium according to decision-makers' preferences. Two environmental criteria (water footprint and global warming potential), two techno-economic criteria (energy return on investment and levelized cost of fuel), and one social criterion (public acceptance) form the basis of this assessment. Once the criteria are determined, a MCDA method that combines the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is used to prioritize the alternatives. The AHP is used to determine the weights of the criteria (eight weight distributions are studied), then the TOPSIS method is used to rank the different bioethanol options. The proposed method evaluates four bioethanol production scenarios, i.e. four feedstocks viable for bioethanol production (wheat, sugar beet, miscanthus, and forest residue). Miscanthus-based bioethanol is regarded as the sustainable alternative in most of the cases studied, with bioethanol from forest residue coming second. Bioethanol derived from wheat and sugar beet is considered a sustainable solution when the levelized cost of fuel criterion is given a higher weight than the remaining criteria. The suggested method is generic, meaning that other alternatives can be studied. The main contribution of this master thesis is to combine quantitative criteria with a qualitative criterion in a MCDA method to assess the most sustainable alternative among four bioethanol production scenarios. The proposed method enables to determine the outcome of decision-making based on the preferences of different stakeholders, through the use of different weight distributions.

Keywords Analytic hierarchy process, Bioethanol, Multi-criteria decision analysis, Technique for order preference by similarity to ideal solution

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With profound gratitude,

Arthur

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Nomenclature

AHP	Analytic Hierarchy Process
BE	Belgium
CCC	Climate Change Contribution
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
DDGS	Distillers' Dry Grains and Solubles
ELECTRE	ELimination Et Choix Traduisant La REalité
EROI	Energy Return On Investment
EtOH	Ethanol
ET	Evapotranspiration
FR	France
GE	Germany
GHG	Greenhouse Gas
GWP	Global Warming Potential
g DM	Gram of Dry Matter
g EtOH	Gram of Ethanol
H_2O	Chemical formula of water

iLUC	Indirect Land Use Change
LCOF	Levelized Cost Of Fuel
LUC	Land Use Change
L EtOH	Liter of ethanol
L H_2O	Liter of water
LHV	Lower Heating Value
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
N_2O	Nitrous oxide
PA	Public Acceptance
PROMETHEE	Preference Ranking Organization METHod for Enrichment Evaluations
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UK	United Kingdom
USA	United States of America
WF	Water Footprint

Introduction

Greenhouse gas (GHG) emissions from transport is responsible for about one-fifth of Belgium's total GHG emissions (Service Changements climatitques, n.d.-b). This important emission level can be attributed to the sector's dependence on petroleum-based fuels. Beside from having a direct impact on global warming through the increase of GHGs concentration in the atmosphere, this reliance has led to adverse social, political and other environmental impacts. To address these pressing concerns and foster a transition towards a more sustainable future, it is paramount to reduce dependence on fossil fuels and embrace renewable alternatives. Bioethanol is one of the numerous alternatives being considered as it is regarded as a promising gasoline substitute to mitigate climate change and avoid dependence on unpredictable foreign suppliers.

Bioethanol can be produced using either conventional or advanced biofuel technologies. Conventional technologies include bioethanol produced from sugar- and starch-based crops, originating from edible biomass, and are also known as first-generation bioethanol. Advanced technologies enable the production of bioethanol from biomass that possesses lignocellulosic content. This second-generation bioethanol, also known as cellulosic ethanol, is produced from non-food crops such as wood chips, perennial grasses, crop residues and municipal wastes. Regardless of the bioethanol technologies used to produce bioethanol, the bioethanol process have to undergo the same several main treatment steps, which involves pre-treatment, extraction of fermentable sugars and fermentation (Chin, 2013).

The selection of feedstock for bioethanol production depends on location and dominant agricultural product. Whether it's corn, wheat and sugar beet in Europe, sugar cane in Brazil, or corn in the United States, first-generation bioethanol dominates the global bioethanol market. However, the conversion of food crops into bioethanol has raised concerns about possible food shortages. Therefore, second-generation bioethanol has gained attention as it could avoid the food versus fuel debate. Nevertheless, there are other concerns related to increasing the production of bioethanol, such as the risk of increase GHG emissions through direct and indirect land use change from production of bioethanol feedstocks, along with the risks of deterioration of water resources, land, and forests, for which second-generation bioethanol can also be concerned (Jeswani *et al.*, 2020). Environmental impacts of bioethanol production is dependent on the feedstock used, the agricultural methods, and the conversion processes, for which the literature is rich in life cycle analyses (LCAs) attesting to this. But LCAs have shown to be insufficient to assess whether a bioethanol production scenario is sustainable or not. Nor are techno-economic assessments sufficient.

The specific challenges in the evaluation of bioethanols require models that are capable of weighing environmental, techno-economic, and social criteria in relation to one another. In this regard, multi-criteria decision analysis (MCDA) has become a benchmark approach used to address decision-making processes related to renewable energies, as various factors are needed to assess for sustainable technologies. MCDA is a tool that enables to rank different alternatives based on several criteria and their relative importance. There are various methods such as outranking, preferential ranking, or distance-based methods for assessment and decision-making of suitable alternatives, and a number of studies have used these methods to select from a range of biofuel options.

Haase *et al.* (2020) conducted a comparative sustainability assessment of straw- and wood-based bioethanol using the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method, considering ecological, economic, and social dimensions. Firouzi *et al.* (2021) used multiple MCDA methods, including TOPSIS, to evaluate eleven potential sources of biofuel production in the Guilan province of Iran, based on ten criteria. An assessment of several biodiesel feedstocks using various MCDA methods, among which the TOPSIS method, was performed in Anwar (2021). The latter article concentrated its assessment on criteria based on economic, technical, and environmental aspects. Another paper used the multi-criteria analysis framework to evaluate four biofuel options (biodiesel, bioethanol, biogas, and synthetic biodiesel) in Belgium (Turcksin *et al.*, 2011). The common feature of the above-mentioned articles is their lack of transparent evaluation of the criteria, as the focus is on conducting the MCDA method and presenting the results. The aim of this master thesis is to provide a transparent, multi-criteria approach to the assessment of different biomass sources for bioethanol production in Belgium.

Two environmental criteria (water footprint and global warming potential), two techno-economic criteria (energy return on investment and levelized cost of fuel), and one social criterion (public acceptance) form the basis of this assessment. Four bioethanol production scenarios are considered, two of which are first-generation bioethanol (i.e. wheat- and sugar beet-based) well established in the Belgian bioethanol market, and two of which are second-generation bioethanol (i.e. miscanthus- and forest residue-based), not widespread to date but with the potential to become viable (PNEC, 2021). The MCDA method conducted in this work is a combination of the analytic hierarchy process (AHP) and TOPSIS method. The AHP is used to assign weights to the criteria, and the TOPSIS method is used to rank the bioethanol options.

In the first chapter, the multi-criteria framework conducted in this work is motivated. An introduction to the concept of MCDA and its applications in the context of decision-making for renewable technologies is given. The AHP method used to evaluate the relative importance of each criterion is described in details, along with the TOPSIS method. The motivation for basing the assessment on a combined AHP-TOPSIS method is presented. The second chapter is dedicated to defining the five criteria under consideration, and to provide a transparent process. This involves the specification of the methods used to conduct the evaluation of the criteria along with a clear presentation of the results. In the third chapter, the outcomes of the MCDA for eight weight distribution scenarios and an additional case accounting for uncertainties in the public acceptance criterion are presented and discussed. The different weight allocation scenarios allow the preferences of different decision-makers to be taken into account, and therefore examine which source of biomass for bioethanol production would be considered sustainable under different perspectives. The fourth and final chapter is dedicated to drawing a parallel with a master thesis from the Faculty of Philosophy, Arts and Letters at UCLouvain, as part of the OIKOS initiative. This chapter discusses the use of biomass as an energetic vector within a philosophical framework, addressing the notion of the temporality of plant life.

Chapter 1

Multi-criteria framework

Evaluating several bioethanol production routes implies using a method able to take into account different dimensions. To meet this requirement, multi-criteria decision analysis (MCDA) was the chosen approach as it offers a robust framework for selecting the most appropriate option based on multiple (often conflicting) criteria. The aim of this chapter is to provide a comprehensive presentation of the decision-making process conducted in this work. Through this chapter, readers will gain a thorough understanding of the approach used to evaluate and rank the feedstock options (i.e. wheat, sugar beet, miscanthus, and forest residue) based on specific criteria (i.e. water footprint, global warming potential, energy return on investment, levelized cost of fuel, and public acceptance).

The chapter begins with a general introduction section that provides a comprehensive overview of the concept of MCDA and its relevance in making informed choices for bioethanol production. The AHP method used to weight these criteria is then detailed, elucidating the approach adopted to assign relative importance to each criterion. Eventually, the TOPSIS method applied to rank the alternatives is presented.

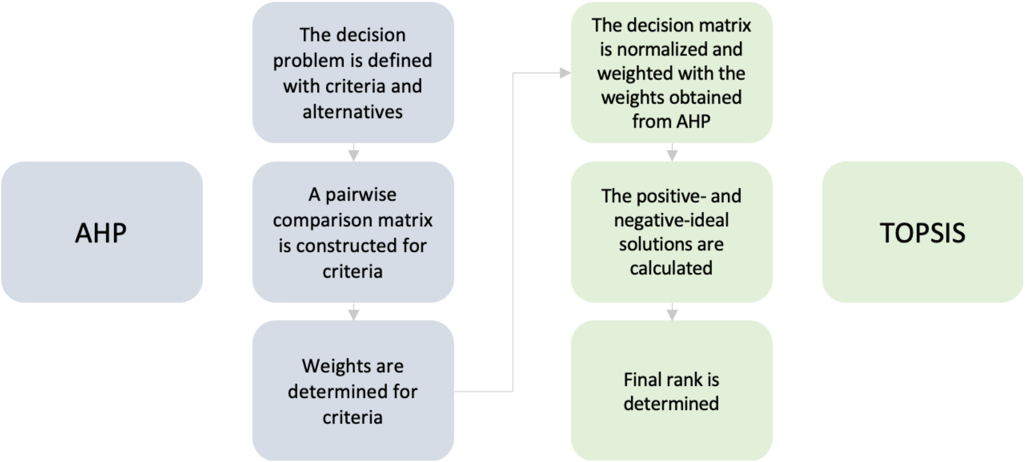
1 MCDA: introduction

Multi-Criteria Decision Analysis (MCDA), also referred to as Multi-Criteria Decision-Making (MCDM), is a decision-making approach that enables to consider various criteria together as a mean to rank or choose between available options. MCDA methods can handle both quantitative and qualitative criteria, offering a flexible tool for decision-makers to make well-balanced decisions when confronted to problems requiring these two forms of data. In addition, in these problems, weights are attributed to the criteria determining the importance of each criterion relative to one another. Multi-criteria methods find applications in various fields, including renewable energies.

In most sectors, renewable energies are set to replace fossil-based energies. Integrating new renewable energies requires consideration of a multitude of conflicting aspects, i.e. environmental, techno-economic, and social factors (Diakoulaki and Karangelis, 2007). As a matter of fact, and as well expressed in Abu Taha and Daim (2013), "renewable energy decision-making can be viewed as a multiple criteria decision-making problem". Thus, using MCDA appears to be an appropriate tool in the ranking process of several biomass for the production of bioethanol. Indeed, multi-criteria framework provides a technical-scientific decision-making instrument that is able to support choices based on priorities granted to specific criteria in the renewable energy sector (Cavallaro, 2010).

When tackling a multi-criteria problem, the choice of method to be used is an important issue. There exists various distinct MCDA methods with different aggregating techniques, which the most important are Analytic Hierarchy Process (AHP), ELimination Et Choix Traduisant La REalité[1] (ELECTRE), Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE), and Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) (Taherdoost and Madanchian, 2023). The literature discusses which method is best to use for a given problem, however, all the methods cited have been used numerous times for renewable decision problems (Abu Taha and Daim, 2013). An approach combining the AHP and TOPSIS method was chosen in this work, with the AHP used to determine the weights of the criteria through pairwise comparisons and TOPSIS is used to obtain the final ranking, as TOPSIS extended versions for interval data (which is used) are well documented in the literature (Roszkowska, 2011 ; Jahanshahloo *et al.*, 2006). This combination has been tested and approved in different studies (Berdie *et al.*, 2017 ; Kumar *et al.*, 2020 ; Tariq *et al.*, 2020). Whatever the method applied, MCDA problems share the same general problem formulation as described in the subsequent section. A schematic of the procedure conducted throughout this work is illustrated in **Figure 1.1**.

Figure 1.1: Illustration of the combined AHP and TOPSIS approach conducted in this work. Adapted from Sharma *et al.* (2020).



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[1] Translated from french as "ELimination and Choice Expressing REality".

1.1 General problem formulation

Multi-criteria problem-solving entails the construction of a decision matrix (Roszkowska, 2011). This matrix can be expressed as

$$\begin{array}{cccccc} & \mathbf{C}_1 & \mathbf{C}_2 & \dots & \mathbf{C}_m \\ \mathbf{A}_1 & x_{11} & x_{12} & \dots & x_{1m} \\ \mathbf{A}_2 & x_{21} & x_{22} & \dots & x_{2m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_n & x_{n1} & x_{n2} & \dots & x_{nm} \end{array} \tag{1.1}$$

together with the weight vector w written as

$$w = \begin{pmatrix} w_1 & w_2 & \dots & w_m \end{pmatrix}. \tag{1.2}$$

In the matrix representation (see equation **1.1**), $\mathbf{A}_i$ $(i = 1,2,...,n)$ denotes the alternatives under consideration in the decision-making process, i.e. the feedstock options evaluated for bioethanol production. Forming the columns of the matrix, $\mathbf{C}_j$ $(j = 1,2,...,m)$ represents the criteria influencing the decision-making process. The core of the matrix is made up of the x_{ij} terms, referring to the performance ratings of alternatives $\mathbf{A}_i$ with respect to criteria $\mathbf{C}_j$ (Jahanshahloo *et al.*, 2006). Each term w_j $(j = 1,2,...,m)$ in the weight vector expressed in equation **1.2** corresponds to the relative importance associated with the j-th criterion. The weight vector responds to the following condition (Roszkowska, 2011) :

$$\sum_{j=1}^{m} w_j = 1. \tag{1.3}$$

The elements of the decision matrix can be fixed or presented in interval form. In general, the matrix elements do not have the same units, due to the different nature of the criteria. This calls for the use of a normalization technique, which renders the matrix data dimensionless. Then, the mathematical development of the method can be used to rank the different alternatives according to their assigned score. In the context of this research work, the TOPSIS method is applied and will be presented in detail in section 5.

2 Weighting method: AHP

The issue of assigning weights to criteria is a common challenge encountered in various multi-criteria decision analysis methodologies (Odu, 2019). Given the substantial influence that criteria weights have on the results of decision-making, it is crucial to meticulously evaluate the relative importance of each criterion among the set of criteria. The AHP method introduced by Saaty (1977) is used in this work to assign weights to the considered criteria. This weighting method is based on pairwise comparisons. It enables the decision-maker to compare each criterion with the others and determine its relative importance in terms of a percentage or score between 0 and 1. The steps involved in the process are described hereafter:

Step 1 - Construction of the pairwise comparison matrix

The idea is to build the pairwise comparison matrix, which can be pictured as follows:

$$\begin{array}{ccccc} & \mathsf{C}_1 & \mathsf{C}_2 & \dots & \mathsf{C}_n \\ \mathsf{C}_1 & c_{11} & c_{12} & \dots & c_{1n} \\ \mathsf{C}_2 & c_{21} & c_{22} & \dots & c_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathsf{C}_n & c_{n1} & c_{n2} & \dots & c_{nn} \end{array} \tag{1.4}$$

This matrix is a squared $n \times n$ matrix, where n is the number of criteria, and in which each element c_{ij} indicates the relative importance of criteria i as compared to criteria j. These involve comparisons, thus assigning numerical values to each element of the matrix. Depending on the importance of a criterion over another, the possible numerical values that can be assigned are summarized in **Table 1.1**.

Table 1.1: Scale of relative importance. Adapted from Saaty (1977).

Numerical values	Order of importance
9	Extreme importance
7	Demonstrated importance
5	Strong importance
3	Moderate importance
1	Equal importance
2,4,6,8	Intermediate judgments

Using the AHP weighting method, the criteria are compared in pairs. Thus, the number of comparisons c_p can be determined through the following equation:

$$c_p = \frac{n(n-1)}{2}. \tag{1.5}$$

Looking at the given scale for relative importance, an equal importance is assigned through the number 1. Thus, one may find it straightforward that the diagonal in the pairwise comparison matrix is always 1 (see equation **1.4**). Moreover, the lower left values of this matrix are reciprocal of the upper right values to ensure that the matrix remains consistent. Indeed, if criterion i has a certain importance with respect to criterion j, then criterion j has an inverse importance with respect to criterion i. The pairwise comparison matrix can then be pictured as follows:

$$\begin{array}{ccccc} & \mathsf{C}_1 & \mathsf{C}_2 & \dots & \mathsf{C}_n \\ \mathsf{C}_1 & 1 & c_{12} & \dots & c_{1n} \\ \mathsf{C}_2 & 1/c_{12} & 1 & \dots & c_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathsf{C}_n & 1/c_{1n} & 1/c_{2n} & \dots & 1 \end{array} \tag{1.6}$$

Step 2 - Calculate the criteria weight

Once the pairwise comparison matrix is constructed, the second step aims to calculate the criteria weight. This is achieved through the process of normalization, where each element in the matrix is divided by the sum of its respective column, i.e.

$$n_{ij} = \frac{c_{ij}}{\sum_{i=1}^{n} c_{ij}} \qquad \text{for} \quad j = 1, 2, ..., n. \tag{1.7}$$

The weight of each criterion is then computed as

$$w_i = \frac{\sum_{j=1}^{m} n_{ij}}{m} \qquad \text{for} \quad i = 1, 2, ..., n. \tag{1.8}$$

Step 3 - Assessment of the consistency ratio

In the ultimate phase of the pairwise comparison process, a consistency ratio is computed to ensure a degree of coherence in the judgments made while constructing the matrix. The ratio, referred to as CR, is computed as follows :

$$\mathsf{CR} = \frac{\mathsf{CI}}{\mathsf{RI}} \tag{1.9}$$

where CI is known as the consistency index and RI the random index. CR needs to be less than 0.1 for the obtained criteria weights to be considered coherent. Otherwise, it indicates a lack of coherence in the judgments made.

Table 1.2: Random index. Adapted from Saaty (1980).

Order	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The RI depends on the number of criteria considered. It can be found in **Table 1.2**.

The CI is computed through a set of operations. The first operation consists in multiplying each term c_{ij} of the pairwise comparison matrix with the relevant weight w_j. Then, the idea is to sum up all the elements per row. This can be mathematically represented as follows:

$$s_i = \sum_{j=1}^{n} c_{ij} * w_j \qquad \text{for } i = 1, 2, ..., n. \tag{1.10}$$

Let λ_{max} be the average of the s_i values. This is obtained as

$$\lambda_{max} = \frac{\sum_{i=1}^{n} s_i}{n} \tag{1.11}$$

The consistency index can then be computed as

$$\text{CI} = \frac{\lambda_{max} - n}{n - 1} \tag{1.12}$$

3 Ranking method: TOPSIS

As mentioned earlier, the MCDA method that has been chosen for the assessment of the different bioethanol production routes is TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). Moreover, the data used is presented in the form of intervals. Indeed, it is sometimes difficult to determine the exact value of the criteria. Working with interval data allows for the representation of uncertainty associated with different criteria. It acknowledges that the values of certain indicators may vary within a certain range, rather than being fixed or deterministic. This flexibility enables a more realistic assessment of the alternatives. Furthermore, interval data offers a way to handle imperfect information more effectively. The intervals encompass plausible values based on available data or expert knowledge, thus accommodating uncertainties and reducing the potential bias caused by inaccurate or incomplete data (Roszkowska, 2011).

The TOPSIS method was first presented from Hwang and Yoon (1981). The basic principle of this technique is that the best candidate should have the farthest distance from the negative-ideal solution and the shortest distance from the positive-ideal solution (Jahanshahloo *et al.*, 2006). The idea of the method is to assign a performance score to each alternative ranging from 0 to 1 based on the Euclidean distances between each alternative on the one hand, and the positive- and negative-ideal solution on the other. However, the technique was first developed for deterministic values in the decision matrix (see equation **1.1**). Jahanshahloo *et al.*, (2006) presented an algorithmic method which extends the TOPSIS method for decision-making problems with interval data. In this case, the decision matrix can be expressed as

$$\begin{array}{cccccc} & \mathsf{C}_1 & \mathsf{C}_2 & \cdots & \mathsf{C}_m \\ \mathsf{A}_1 & [x_{11}^l, x_{11}^u] & [x_{12}^l, x_{12}^u] & \cdots & [x_{1m}^l, x_{1m}^u] \\ \mathsf{A}_2 & [x_{21}^l, x_{21}^u] & [x_{22}^l, x_{22}^u] & \cdots & [x_{2m}^l, x_{2m}^u] \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathsf{A}_n & [x_{n1}^l, x_{n1}^u] & [x_{n2}^l, x_{n2}^u] & \cdots & [x_{nm}^l, x_{nm}^u] \end{array} \tag{1.13}$$

where l and u stands for lower and upper values, respectively. The following steps outline the procedure:

Step 1 - Calculate the normalized decision matrix

The normalized values n_{ij}^l and n_{ij}^u are computed as

$$n_{ij}^l = \frac{x_{ij}^l}{\sqrt{\sum_{i=1}^n((x_{ij}^l)^2 + (x_{ij}^u)^2)}} \quad \text{for } i = 1, 2, ..., n \text{ and } j = 1, 2, ..., m. \tag{1.14}$$

$$n_{ij}^u = \frac{x_{ij}^u}{\sqrt{\sum_{i=1}^n((x_{ij}^l)^2 + (x_{ij}^u)^2)}} \quad \text{for } i = 1, 2, ..., n \text{ and } j = 1, 2, ..., m. \tag{1.15}$$

The normalized decision matrix is then obtained:

$$\begin{array}{cccccc} & \mathsf{C}_1 & \mathsf{C}_2 & \cdots & \mathsf{C}_m \\ \mathsf{A}_1 & [n_{11}^l, n_{11}^u] & [n_{12}^l, n_{12}^u] & \cdots & [n_{1m}^l, n_{1m}^u] \\ \mathsf{A}_2 & [n_{21}^l, n_{21}^u] & [n_{22}^l, n_{22}^u] & \cdots & [n_{2m}^l, n_{2m}^u] \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathsf{A}_n & [n_{n1}^l, n_{n1}^u] & [n_{n2}^l, n_{n2}^u] & \cdots & [n_{nm}^l, n_{nm}^u] \end{array} \tag{1.16}$$

The normalized interval [n_{ij}^l,n_{ij}^u] belongs to the interval [0,1].

Step 2 - Calculate the weighted normalized decision matrix

Recall the weight vector $w = \begin{pmatrix} w_1 & w_2 & ... & w_m \end{pmatrix}$ from equation **1.2**. Taking into account the relative importance of each criterion, the weighted normalized decision matrix can be constructed as follows :

$$v^l_{ij} = w_j n^l_{ij} \quad \text{for } i = 1, 2, ..., n \text{ and } j = 1, 2, ..., m. \tag{1.17}$$

$$v^u_{ij} = w_j n^u_{ij} \quad \text{for } i = 1, 2, ..., n \text{ and } j = 1, 2, ..., m. \tag{1.18}$$

where w_j is the weight of the j-th criterion and $\sum_{j=1}^{m} w_j = 1$ (as stipulated in equation 1.3). The weighted normalized decision matrix is then obtained:

$$\begin{array}{ccccc} & \mathsf{C}_1 & \mathsf{C}_2 & \dots & \mathsf{C}_m \\ \mathsf{A}_1 & [v^l_{11}, v^u_{11}] & [v^l_{12}, v^u_{12}] & \dots & [v^l_{1m}, v^u_{1m}] \\ \mathsf{A}_2 & [v^l_{21}, v^u_{21}] & [v^l_{22}, v^u_{22}] & \dots & [v^l_{2m}, v^u_{2m}] \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathsf{A}_n & [v^l_{n1}, v^u_{n1}] & [v^l_{n2}, v^u_{n2}] & \dots & [v^l_{nm}, v^u_{nm}] \end{array} \tag{1.19}$$

Step 3 - Determine the positive- and negative-ideal solutions

The positive-ideal solution A^+ and the negative-ideal solution A_- are defined as

$$A^+ = \{v_1^+, v_2^+, ..., v_m^+\} = \Big\{(\underset{i}{max} \ v^u_{ij} \mid j \in I), (\underset{i}{min} \ v^l_{ij} \mid j \in J)\Big\} \tag{1.20}$$

$$A^- = \{v_1^-, v_2^-, ..., v_m^-\} = \Big\{(\underset{i}{min} \ v^l_{ij} \mid j \in I), (\underset{i}{max} \ v^u_{ij} \mid j \in J)\Big\} \tag{1.21}$$

where I is associated with benefit criteria and J with cost criteria.

step 4 - Calculate the distance of each alternative from ideal solutions

The distance of each alternative from the positive-ideal solution is calculated as

$$d_i^+ = \sqrt{\sum_{j=1}^{m} (v^l_{ij} - v_j^+)^2 + \sum_{j=1}^{m} (v^u_{ij} - v_j^+)^2} \qquad \text{for } i = 1, 2, ..., n. \tag{1.22}$$

and similarly, the distance of each alternative from the negative-ideal solution is calculated as

$$d_i^- = \sqrt{\sum_{j=1}^{m}(v_{ij}^u - v_j^-)^2 + \sum_{j=1}^{m}(v_{ij}^l - v_j^-)^2} \qquad \text{for } i = 1, 2, ..., n. \tag{1.23}$$

Step 5 - Calculate the performance score

The performance score P_i of alternative A_i is defined as

$$P_i = \frac{d_i^-}{d_i^- + d_i^+} \qquad \text{for } i = 1, 2, ..., n. \tag{1.24}$$

where $0 \leq P_i \leq 1$. The alternatives can then be ranked in descending order based on the value of P_i.

Chapter 2

Environmental, techno-economic, and social dimensions

The purpose of this chapter is to report on the data used in the MCDA in order to ensure a transparent process. This involves referencing the various studies carried out in the literature for each data item, being critical on the values found, explaining in detail the methods applied, the assumptions made and the geographical location of the studies carried out, as these have a direct influence on the data associated with the considered indicators, i.e. water footprint, global warming potential, energy return on investment, levelized cost of fuel, and public acceptance. Moreover, additional computations and assumptions where made when needed within this work as well, these are further specified in this chapter. Thus, this chapter delves into a comprehensive examination of the five indicators related to the production of bioethanol using wheat, sugar beet, miscanthus, and forest residue as feedstocks. The use of these indicators enables environmental, techno-economic, and social aspects to be taken into account in the multi-criteria assessment that follows.

The chapter is structured into two main sections. First, an introduction to the five indicators is achieved through comprehensive and concise definitions. Second and last, the results obtained for each of these indicators are presented and discussed, along with intuitive and useful information on the methods applied to achieve these results.

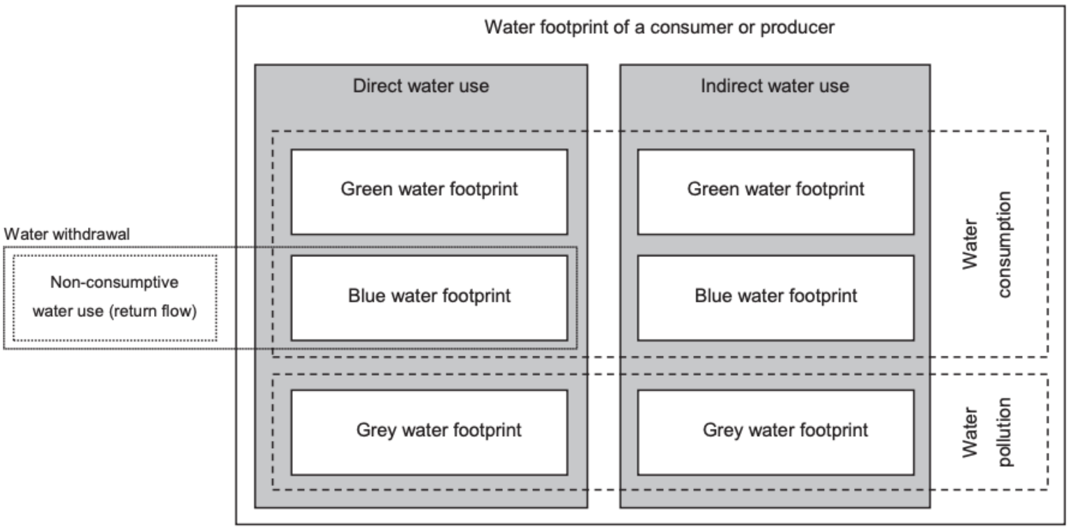
1 Definitions

In this section, the reader is invited to gain an insight of the various indicators, used as criteria in the multi-criteria evaluation, through small definitions.

1.1 Water footprint - WF

The concept of water footprint is not to be confused with that of water withdrawal. While water withdrawal focuses on the direct extraction of water from surface and groundwater, the water footprint considers the total amount of freshwater used, including both direct and indirect water use in the production and consumption of goods and

Figure 2.1: This diagram illustrates the elements comprising a water footprint. It highlights that the non-consumptive portion of water withdrawals, referred to as the "return flow," is not considered within the water footprint. In addition, it demonstrates that unlike the metric of 'water withdrawal', the 'water footprint' encompasses green and grey water, along with the indirect water-use component. The schematic is taken from Hoekstra *et al.* (2011).



services (see **Figure 2.1**). The water footprint can be broken down into three components that work together to create a complete picture of water use: blue, green, and grey. Blue water is surface and groundwater consumed, e.g. water applied for irrigation that evaporated during crop growth (Mekonnen and Hoekstra, 2011 ; Gerbens-Leenes *et al.*, 2008). The term 'consumed' is associated to water losses due to evaporation or water returned to another basin or the sea or water absorbed in a product. Green water is rainwater consumed during the production process, e.g. during crop growth (Gerbens-Leenes *et al.*, 2008). Unlike blue and green water, grey water is not associated to water consumption, instead it refers to pollution. It can be defined as the volume of freshwater needed to assimilate pollutants in order to maintain a certain level of water quality based on determined standards (Hoekstra *et al.*, 2011). However, most studies don't include this last component when accounting for the water footprint related to the production of the crops used to manufacture bioethanol. When included, the grey water contribution will be mentioned and discussed but will not be used in the MCDA.

The water needed to produce water-intensive commodities was first known as virtual water (Allan, 1997). As a matter of fact, the concept of water footprint is derived from that of virtual water. Both can be defined as the water embedded in a product, but not in the real sense; rather, in the virtual sense (Hoekstra, 2003). These two concepts are sometimes confused with each other, but care must be taken when mentioning them, as the notion of virtual water is broader than that of water footprint. There are two practical uses of virtual water, and the water footprint can be seen as one of them. While a product's water footprint provides information about its environmental impact, the second practical application of the virtual water concept is as a tool achieving water security and efficient water use (Hoekstra, 2003). The second use will not be retained in this work. Moreover, there exists two approaches when it comes to establishing a quantitative definition of the water footprint; whether it adopts a producer or consumer standpoint. The first approach defines the water footprint as the amount of the actual water required to manufacture the product, whereas the second approach defines the water footprint of a product as the volume of water that would have been needed to generate the product at the location where it is utilized (Hoekstra, 2003). In this work, the second approach is not considered. This is because the assessment made in this work focuses on the impacts of producing and consuming bioethanol in Belgium, and no consideration of producing bioethanol in Belgium for other countries is made. Hence, the water footprint is the main emphasis of this work and is defined here as the amount of freshwater consumed for the manufacture of a good at the specific place it was produced (Hoekstra and Chapagain, 2007). The water footprint is here expressed in L H_2O (L EtOH)$^{-1}$.

1.2 Global warming potential - GWP

The global warming potential (GWP) impact is an indicator used to assess the greenhouse gases (GHGs) emission associated with the production of renewable energies in order to estimate the GHG savings from using fossil fuels. It enables to account for the different gases using a single metric, CO_2-equivalent (often written as CO_2eq). These gases include, but are not restricted to, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The global warming potential values of these three main GHGs, over different time periods, are summarized in **Table 2.1**. These values were developed to compare the contribution to global warming of different GHGs. To be precise, the global warming potential of a gas is defined as the amount of energy the emissions of 1 ton of that gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (US EPA, 2023).

Table 2.1: Main greenhouse gas GWPs given for 20-year, 100-year, and 500-year time horizons. Adapted from IPCC, Sixth Assessment Report (AR6) (2021).

Name	Formula	GWP-20	GWP-100	GWP-500
Carbon dioxide	CO_2	1	1	1
Methane	CH_4	81.2	27.9	7.95
Nitrous oxide	N_2O	273	273	130

As an indicator used in diverse MCDAs related to renewables, and more commonly in life cycle assessments (LCAs), the global warming potential associated to the production of bioethanol is also reported as the GHG balance or contribution to climate change (CCC) (Abdel-Basset *et al.*, (2021) ; Baudry *et al.*, (2018) ; Turcksin *et al.*, (2011)). Indeed, some authors prefer to use another designation to avoid confusion with the global warming potential of gases. It is therefore important for the reader to distinguish between the global warming potential, here used to assess the impact on global warming of bioethanol production due to unavoidable emissions, from the global warming potential of GHGs, which gives an indication of the contribution of a specific gas to global warming relative to CO_2 (and which forms the basis of the assessment of GHG emissions of the production of bioethanol as CO_2 isn't the unique GHG concerned). The global warming potential is here expressed in g CO_2eq (L EtOH)$^{-1}$.

1.3 Energy return on investment - EROI

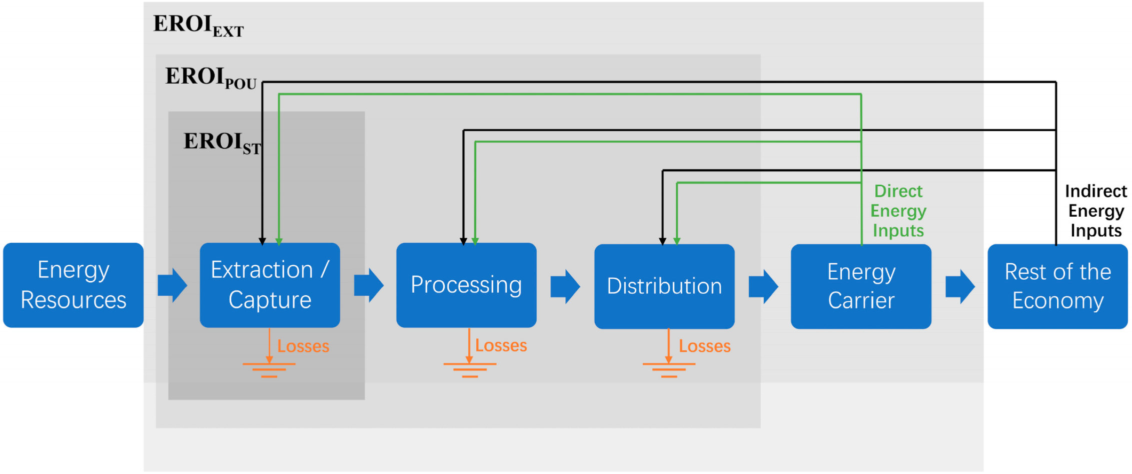
This indicator translates a return on investment from an energetic point of view. The EROI concept must not be confused with conversion efficiency, e.g. converting diesel into electricity. The EROI is defined as the ratio between the total energy produced (E_{produced}) and the total energy invested (E_{invested}), thus required, to accomplish the production over the entire life cycle of the system under consideration, i.e.

$$\text{EROI} = \frac{E_{\text{produced}}}{E_{\text{invested}}} \tag{2.1}$$

As the numerator and denominator are expressed in the same units the ratio so derived is dimensionless, e.g. 5:1 which can be read "five to one". This would mean that a process delivers 5 Joules on an investment of 1 Joule. An EROI below 1:1 would indicate that a system requires more energy than it produces. Such a system should be avoided. However, in some cases it could be considered useful to deliver a specific energy carrier in particular demand, for instance, within the industrial food system. This discussion is beyond the scope of this work.

Although equation **2.1** appears to be simple, its application involves both theoretical and practical challenges that necessitate a meticulous clarification of the spatial and energetic boundaries considered. **Figure 2.2** shows the three main EROIs acknowledged in the literature. The standard EROI (EROI_{ST}) accounts for the energy needed in the extraction process (i.e. for the harvesting process in the case of biofuels). However, this EROI is not relevant for biofuels as the distribution and conversion stage are often larger than (or at least non-negligible from) the initial stage of harvesting. Instead, the point of use EROI (EROI_{POU}) is more commonly used. This EROI accounts for all the energy needed for processing the fuel and delivering it to the consumer. The EROI reported in the results section follow this EROI definition. Moreover, an extended EROI (EROI_{EXT}) was introduced to account for the energy required to produce the machinery and devices used to build, operate, and maintain a plant (e.g. a bioethanol lant) or a transportation facility (e.g. a truck) (Castro and Capellán-Pérez, 2020).

Figure 2.2: Standard EROI (EROI$_{\text{ST}}$), point of use EROI (EROI$_{\text{POU}}$), and extended EROI (EROI$_{\text{EXT}}$). From Feng *et al.* (2018).



1.4 Levelized cost of fuel - LCOF

The levelized cost of fuel (LCOF) is an indicator used in this work to measure the average cost of producing one liter of bioethanol over the lifetime of a bioethanol plant. The LCOF is computed as follows:

$$\text{LCOF} = \frac{\text{NPV of Total Costs Over Lifetime}}{\text{NPV of Bioethanol Produced Over Lifetime}} \tag{2.2}$$

where NPV denotes the "Net Present Value". The total costs of bioethanol plant projects include:

- Capital costs (CAPEX)
- Fixed operating costs (Fixed OPEX)
- Variable operating costs (Variable OPEX)

CAPEX gathers investment costs, i.e. plant equipment, installation, site preparation, etc. OPEX is separated into two costs, with Fixed OPEX which includes salaries, plant maintenance, insurance, and other considered "fixed" costs, while Variable OPEX are costs linked to feedstock prices, utilities and chemicals.

The total output is the sum of all the "power" generated (P), i.e. the number of liters produced during the lifetime of the bioethanol plant (n). Another important factor to be considered in the equation is the discount rate (r). Equation **2.2** can be expressed in the following mathematical form:

$$\text{LCOF} = \frac{\sum_{t=1}^{n} \frac{\text{CAPEX}+\text{Fixed OPEX}_t+\text{Variable OPEX}_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{P_t}{(1+r)^t}} \tag{2.3}$$

It is this mathematical formula that is applied to calculate the LCOFs associated with the different bioethanol production scenarios in this work. The LCOF indicator is here expressed in € (L EtOH)$^{-1}$.

1.5 Public acceptance - PA

Public acceptance, as a qualitative criterion, allows to include the public's opinions, attitudes, perceptions and/or preferences in decision-making processes. The concept of public acceptance has gained attention in a context of socio-ecological transition, in which it is acknowledged that a unique technological transformation is insufficient. The transition implies a "radical and non-linear societal change", as stated in Hölscher *et al.* (2017) , which requires that people's participation in decisions related to the transition takes a central role.

Sometimes mistaken with social acceptance, public acceptance is a more restrictive concept than social acceptance which is more general. However, authors have provided the literature with various definitions making the distinction quiet difficult. This being said, authors appear to agree on the three-dimensional approach introduced in Wüstenhagen *et al.* (2007). The three components include :

- *Socio-political acceptance* : refers to the most inclusive form of acceptance from the public, stakeholders, and policy makers.
- *Community acceptance* : refers to the acceptation at a local scale, describing how local stakeholders, residents, and authorities of a community reacts to a given renewable energy project.
- *Market acceptance* : refers to the adoption of a new technology in a market (Fytili and Zabaniotou, 2017).

These three interpretation of social acceptance are interconnected with each other. From this perspective, the distinction between public acceptance and social acceptance appears to be more obvious, with public acceptance being part of the socio-political acceptance component of social acceptance. The main focus in this work is on public perceptions and opinions on the different production routes of bioethanol under consideration.

2 Results and discussion

In what follows, the results of the five indicators for the four bioethanol scenarios are presented and discussed.

2.1 WF

Water requirements for the production of bioethanol can be separated between biomass growth and conversion of biomass. It will be shown that the water required in the conversion stage is negligible compared with that needed to grow the raw materials.

2.1.1 Biomass growth WF

In Belgium, in principle, arable crops such as wheat and sugar beet aren't irrigated. Indeed, more than 95% of agricultural land is rain-fed (Gobin, 2015). This is also true for miscanthus plantations, which do not require irrigation. Thus, estimations of water footprint in Belgium related to crop cultivation doesn't take into account blue water in most cases. Concerning forest residue, blue water is associated with the conversion process which is not considered here as stated earlier. In addition, it is important to note that some authors argue that the WF isn't an appropriate indicator for forest-based products as it does not treat water as an circulating resource (Launiainen *et al.*, 2013). This argument will be discussed later, as it leaves room for interpretation. However, the concept has been used to estimate the water consumption of forest residues, although it must be admitted that studies on water footprint of this feedstock in the literature remain scarce. The water footprints associated with the production of bioethanol from these four feedstock are summarized in **Table 2.2** and account for green water only.

Table 2.2: Green water footprint of bioethanol production from wheat, sugar beet, miscanthus, and forest residue, expressed in L H_2O (L EtOH)$^{-1}$.

Feedstock	Water footprint (L H_2O / L EtOH)		Sources
	Min	Max	
Wheat	737	1152	Based on Gobin (2015) ; Hoekstra *et al.* (2011)
Sugar beet	243	903	Based on Gobin (2015) ; Gerbens-Leenes and Hoekstra (2012) ; Weinberg and Kaltschmitt (2013) ; Foteinis *et al.* (2011) ; Hoekstra *et al.* (2011)
Miscanthus	374	934	Based on Beale *et al.* (1999) ; Clifton-Brown and Lewandowski (2000) ; Khullar *et al.* (2012) ; Cerazy-Waliszewska *et al.* (2019) ; Turner *et al.* (2021)
Forest residue	884	2720	Based on Schyns *et al.* (2017)

From **Table 2.2**, it can be observed that the water footprint of bioethanol varies among the different feedstocks, but also within the same feedstock as minimum and maximum water footprints are sometimes widespread. The wide variations observed can be attributed to disparities in crop yields, energy yields, climatic conditions, and agricultural practices across regions. However, sugar beet appears to have the lowest impact on water consumption and forest residue the largest consumption. In fact, sugar beet has a much inferior water footprint as compared to wheat in terms of amount of water per unit mass (about 7 to 19% of the water footprint associated with wheat cultivation), but this is not perceptible in the data as wheat has a better ethanol conversion yield, thus reducing its impact when expressed in terms of the amount of ethanol produced. Details on the derivation of the reported water footprints are specified for each of the four feedstocks hereafter.

Wheat

Gobin (2015) reported a green water footprint for wheat to be 410 ± 90 m^3 H_2O $(ton)^{-1}$. This water footprint was estimated for the period 1988-2012 which explains the uncertainties due to variability throughout the years. The changes in weather and climate conditions from one year to another impacts crop yields, impacting in consequences water footprints.

From Gobin (2015), the corresponding bioethanol water footprint expressed in L H_2O $(L\ EtOH)^{-1}$ varies from 737 to 1152. This estimation was obtained using the ethanol conversion yield from wheat given by Hoekstra *et al.* (2011), which is 434 L EtOH $(ton)^{-1}$.

Sugar beet

The water footprint of sugar beet was estimated as 77 ± 10 m^3 H_2O $(ton)^{-1}$ in the article written by Gobin (2015) and previously discussed in the wheat water footprint assessment. Another report documented the green WF of sugar beet as 27 m^3 H_2O $(ton)^{-1}$, which is 65% lower than the previous estimate (Gerbens-Leenes and Hoekstra, 2012). This article also computed the grey water footprint for sugar beet in Belgium as being 8 m^3 H_2O $(ton)^{-1}$. The period considered to estimate the water footprint related to the cultivation of sugar beet was taken between 1996 and 2005.

Ethanol conversion yield from sugar beet is 111 L EtOH $(ton)^{-1}$ (Hoekstra *et al.*, 2011). This is similar to the 106 L EtOH $(ton)^{-1}$ for sugar beet reported by Foteinis *et al.* (2011) and close enough from the 96 L EtOH $(ton)^{-1}$ documented in Weinberg and Kaltschmitt (2013). Combining the two opposite conversion factors (i.e. 96 and 111 L EtOH $(ton)^{-1}$) with the estimated green water footprints introduced above, results in a water footprint related to bioethanol produced from sugar beet ranging from 243 and 903 L H_2O $(L\ EtOH)^{-1}$.

Miscanthus

According to Clifton-Brown and Lewandowski (2000), the water requirements for the entire miscanthus plant (both above- and below-ground) varied between 11.5 and 14.2 g DM $(kg\ H_2O)^{-1}$. Values ranging from 2.1 to 4.1 g DM $(kg\ H_2O)^{-1}$ were recorded for shoot biomass production (harvestable biomass). The ranges are due to different miscanthus species studied in their work, however the focus here is made on the results for M. *x giganteus* as it is the most common miscanthus species in Europe. The water requirements for above-ground M. *x giganteus* is measured to be 2.1 g DM $(kg\ H_2O)^{-1}$. Beale *et al.* (1999) estimated the ratio of above-ground biomass to water use for M. *x* *giganteus* under rain-fed conditions at 9.2 and 9.5 g DM (kg H_2O)$^{-1}$ for two different harvest periods. However, for the comparison of the water footprints to be relevant, Clifton-Brown and Lewandowski (2000) estimated that on the same experimental-basis, the water use of M. *x giganteus* would evolve from 2.1 to 6.6 g DM (kg H_2O)$^{-1}$. For this reason, the last cited water footprint is the one that will effectively be retained. Moreover, the two studies did their experiments at different geographical locations; one being in Germany (GE) and the other in the United Kingdom (UK). The results are summarized in **Table 2.3** and expressed as m^3 H_2O (ton)$^{-1}$ to make comparisons with the other feedstock easier.

Table 2.3: Water footprint of M. *x giganteus* expressed in m^3 H_2O (ton)$^{-1}$.

Location	Water footprint (m^3 H_2O / ton)	Sources
GE	152	Clifton-Brown and Lewandowski (2000)
UK	105 ; 109	Beale *et al.* (1999)

From **Table 2.3** and the results presented earlier for wheat and sugar beet, it can be observed that miscanthus has a better water footprint impact than wheat, but slightly higher than sugar beet. However, this does not provide confirmed intuition on miscanthus-based bioethanol water footprint as conversion factors from miscanthus to ethanol have to be considered.

Using liquid hot water (LHW) pretreatment and simultaneous saccharification and fermentation (SSF) of *M. x giganteus*, Khullar *et al.* (2012) documented an ethanol yield of 0.129 g EtOH (g DM)$^{-1}$. An additional research conducted a thorough evaluation of ethanol yields derived from different miscanthus species, including M. *x giganteus*, resulting in an ethanol yield ranging from 0.185 to 0.222 g EtOH (g DM)$^{-1}$ (Cerazy-Waliszewska *et al.*, 2019). In addition, Turner *et al.* (2021) documented an ethanol yield of 0.148 g EtOH (g DM)$^{-1}$ for M. *x giganteus*. The different ethanol yields are resumed in **Table 2.4**.

Table 2.4: EtOH conversion yields from M. *x giganteus* expressed in g EtOH (g DM)$^{-1}$.

EtOH yield (g EtOH / g DM)	Sources
0.129	Khullar *et al.* (2012)
0.185 - 0.222	Cerazy-Waliszewska *et al.* (2019)
0.148	Turner *et al.* (2021)

Observing **Table 2.4**, one can notice that miscanthus offer better EtOH yields than sugar beet, however, these yields remain lower than the yield from wheat.

Forest residues

The water footprint associated with forest residue-based bioethanol remains scarce in the literature. No specific water footprint associated with forest residue was determined for Belgium. However, based on several studies, some approximations were made possible for comparisons. For the southeastern United States, Chiu and Wu (2013) estimated the green water footprint of ethanol produced from forest residue at 401-443 L H_2O (L EtOH)$^{-1}$ on average, with a minium at 270 and a maximum at 1219 L H_2O (L EtOH)$^{-1}$. The obtained data was compared in another paper, which found a water footprint of 476 L H_2O (L EtOH)$^{-1}$ for the same region, considering that the water footprint of roundwood in this region is about 70 m^3/m^3 and a roundwood to bioethanol conversion factor of 6.8 (Schyns *et al.*, 2017). From the latter article, the water footprint of roundwood in Belgium ranges between 130 and 400 m^3/m^3 , which would give a corresponding 884 and 2720 L H_2O (L EtOH)$^{-1}$. The maximum potential water footprint might seem high, but taking into account the difference in water use between the two regions according to Schyns *et al.* (2017), and comparing to the maximum of 1219 L H_2O (L EtOH)$^{-1}$ obtained from Chiu and Wu (2013) is not inconsistent. One can observe that the variation between minimum and maximum water footprint is quite significant, this uncertainty in the assessment of water footprint related to forest residue will be mentioned when interpreting the results of the MCDA. It is important to mention, nevertheless, that while Chiu and Wu (2013) allocated forest evaporation to bioethanol production based on an estimated weight fraction of harvested wood residue in the total above-ground wood mass ($\sim$ 10%), Schyns *et al.* (2017) used the water footprint attributed to roundwood and considered a conversion factor from roundwood to bioethanol. Thus, although the method applied could be questioned, it seems that the water footprint obtained is reasonable as both WFs are similar for the same region (i.e. southeastern United States). Furthermore, as stated earlier, the water footprint as a whole could be questioned when employed for forest-based products.

2.1.2 Industrial WF

In most studies, water consumption in bioethanol plants is omitted from the water footprint calculation as it can be considered negligible compared to the water needs for the agricultural process. Indeed, the needs of water for the conversion process is about 21 litres of water per litre of ethanol delivered (Gerbens-Leenes *et al.*, 2009). Moreover, part of this water is often recovered as ethanol production facilities are designed to reuse water within the plant. Yet, another article estimated the amount of water consumed in Minnesota ethanol plants as ranging from 3.5 to 6 litres of water per litre of ethanol produced (Keeney and Muller, 2006). The latter article also suggested an increase in water use efficiency as the average water consumption in the ethanol facilities considered in their work decreased from 5.8 L H_2O (L EtOH)$^{-1}$ in 1998 to 4.2 L H_2O (L EtOH)$^{-1}$ in 2005. According to Gallagher and Shapouri (2005), old plants used to consume more than 15 L H_2O (L EtOH)$^{-1}$ compared to new plants[1] whose water use ranges from less than 1 to 11 litres of water per litre of ethanol produced, with an average of 4.7 L H_2O (L EtOH)$^{-1}$. This confirms the efforts that have been made among ethanol facilities to

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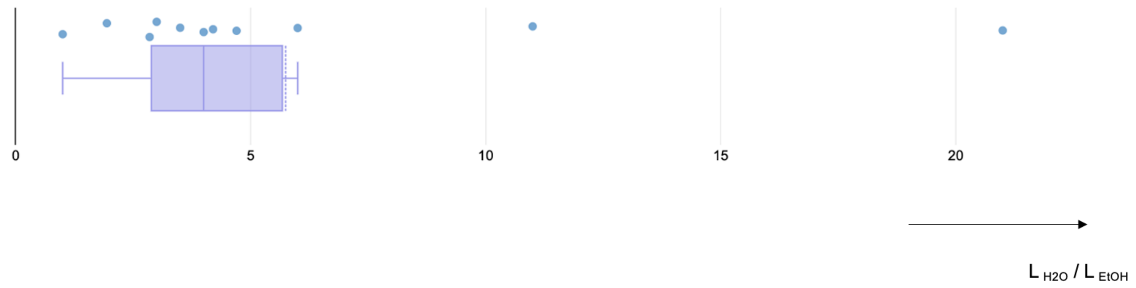
[1] The term "new" should be taken with caution as it refers to a poll conducted in 2002.

Figure 2.3: Industrial WF expressed in L H_2O (L EtOH)$^{-1}$.



reduce their impacts on water consumption. Furthermore, a detailed process design for the conversion of wood chips to ethanol via a thermo-chemical approach estimated an overall water demand of 1.94 L H_2O (L EtOH)$^{-1}$ (Phillips *et al.*, 2007). This conversion process minimized the cooling water demand using air-cooling, which explains the small amount of water needed. Another article tempted minimizing the water requirements of fermentation-based bio-ethanol production in reducing the thermal energy intake, giving a minimum water consumption of 2.85 L H_2O (L EtOH)$^{-1}$ (Pfromm, 2008). However, optimistic assumptions such as complete recycling of the water within the process were made. To resume, Wu and Xu (2018) considered an average consumption of 3 L of water per L of ethanol, which seems to be a well-founded estimate. Data collected from the literature are shown on **Figure 2.3**.

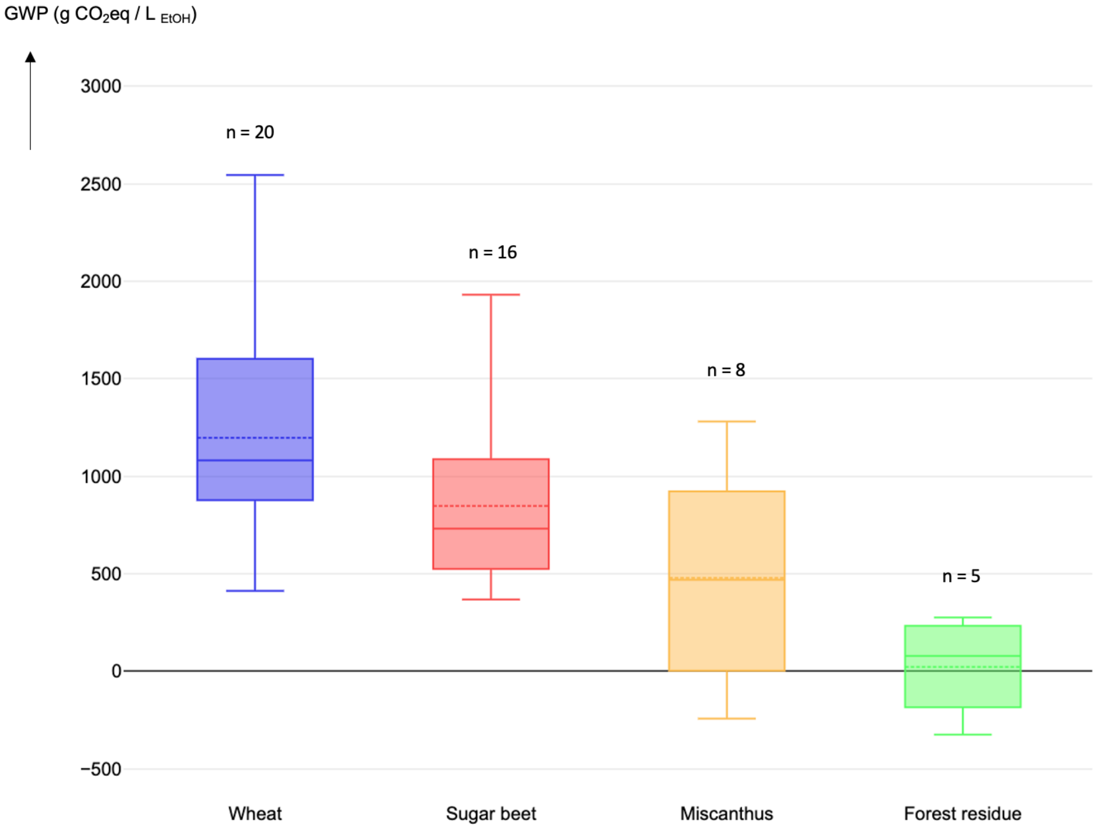
The data collected supports the decision not to take into account water consumption in bioethanol production plants when accounting for the water footprint of these fuels, as it represents a negligible amount compared to the water needed for the biomass to grow.

2.2 GWP

LCA studies often present opposite results when assessing the global warming potential related to the production of bioethanol. This is true for considering different feedstock, as differences in agricultural and conversion processes can result in opposed GHG emissions, but it is even true for the same raw material. This is due to the variations in the assumptions, system boundaries, data sources and allocation methods. Land-use change (LUC) has a considerable impact on global warming, but has not been mentioned since it is unlikely that this kind of practice is applied in Belgium for bioethanol production, the phenomenon having now been recognized. However, it cannot be ruled out that indirect land-use change (ILUC) might occur in the case agricultural land dedicated for food production is diverted to bioethanol production. The aspects influencing the GWP impact are discussed in the subsequent sections. The GWP of bioethanols reported in the reviewed LCA studies is shown in **Figure 2.4**. For further details, see **Appendix A**.

As can be observed in **Figure 2.4**, second-generation bioethanols (i.e. miscanthus

Figure 2.4: GWP of bioethanol produced from wheat, sugar beet, miscanthus, and forest residues. For further details, see **Appendix A**.



and forest residue) show lower global warming potential than first-generation bioethanols (i.e. wheat and sugar beet). The two second-generation bioethanol production scenarios even present negative GWP values. For miscanthus, some studies considered that growing this crop increased the carbon stock in the land used, which resulted in net-negative GHG emissions. In the case of forest residue, it is often assumed that residual lignin is used to co-generate heat and power for the production process, thus avoiding the GHG emissions from the amount of grid electricity that would have been used. This results in credits that are more important than the total GHG emissions from the bioethanol production, resulting in negative GWP which translates a saving of GHG emissions. However, there is a large variation among different studies and between miscanthus and forest residue as feedstocks, with values ranging from -325 to 1281 g CO_2eq (L EtOH)$^{-1}$. In particular, miscanthus shows wide variations with GHG emissions estimated between -234 and 1281 g CO_2eq (L EtOH)$^{-1}$, while forest residue shows what can be considered as narrow variations, with GWP ranging from -325 to 399 g CO_2eq (L EtOH)$^{-1}$. When comparing with first-generation bioethanols, miscanthus shows a maximum GWP which almost reaches the maximum GWP of sugar beet, which gives the impression that both feedstock results in similar GWP. This isn't a wrong conclusion when thinking on an average perspective, with average GWP emissions from the LCAs reviewed resulting in

519 and 753 g CO_2eq (L EtOH)$^{-1}$ for miscanthus and sugar beet, respectively. However first-generation bioethanols doesn't present comparable minimum global warming potential as miscanthus or forest residue, reaching negative values.

Influence of land use change

Land use change emissions related to biofuel production can be accounted as direct (LUC) or indirect (iLUC):

- LUC denotes the process of converting native ecosystems (e.g. forests and grasslands) into agricultural land, or switching crops on existing productive land.
- iLUC occurs when biofuels are produced on existing agricultural land whose previous purpose was food or feed production.

The emissions from LUC can have a significant impact on the GWP of bioethanol. Jeswani *et al.* (2015) evaluated the global warming potential of miscanthus in the UK considering three scenarios: (1) no LUC; (2) conversion of forest land; (3) conversion of grassland. These global warming potential estimates are assessed on a cradle-to-gate basis, with the system credited for the production of co-products. Results are shown on **Figure 2.5** and demonstrate an important increase of the GWP impact when LUC occurs in the production of bioethanol. While no LUC results in a global warming potential of -234 g CO_2eq (L EtOH)$^{-1}$, converting forests into cultivation land for miscanthus would increase the global warming potential to 6885 g CO_2eq (L EtOH)$^{-1}$. Conversion of grassland would result in a GWP of 2279 g CO_2eq (L EtOH)$^{-1}$.

To illustrate these impacts on climate change, **Figure 2.6** compares the GWP values reported for conversion of forests and grasslands into miscanthus fields for bioethanol production to the GWP impact of gasoline per MJ of fuel (GREET calculates 2005 gasoline to have a GWP of 89 g CO_2eq MJ^{-1}). Global warming potentials are here intentionally expressed in these units in order to make a meaningful comparison. We couldn't compare GWP estimates per unit liter, since a liter of ethanol and a liter of gasoline don't have the same energy content. We therefore report these values per unit of energy. The two LUC show a higher impact on climate change than gasoline, with conversion of forest to perennials having a global warming potential which reaches almost 4 times the GWP impact of gasoline. In both cases, no GHG emission savings are possible from replacing gasoline with miscanthus-based bioethanol.

Impacts of different allocation methods

As mentioned earlier, the production of bioethanol often results in the generation of co-products that can be upgraded through different uses. It therefore seems reasonable to give them some credit. It turns out that taking them into account reduces the GWP impact associated with bioethanol production, since these other co-products are also generated, as their name indicates, and must therefore also contribute to these emissions. Thus, using allocation techniques reduces the GWP impact of bioethanol production. There are three main allocation techniques recognized in the literature: either based on mass fraction, energetic content, or economic value. It appears that the

Figure 2.5: Impact of land use change on the global warming potential of miscanthus-based bioethanol. System boundary: cradle-to-gate. Values shown for system expansion with the system credited for co-products (i.e. acetic and lactic acids, and electricity). Adapted from Jeswani *et al.* (2015).

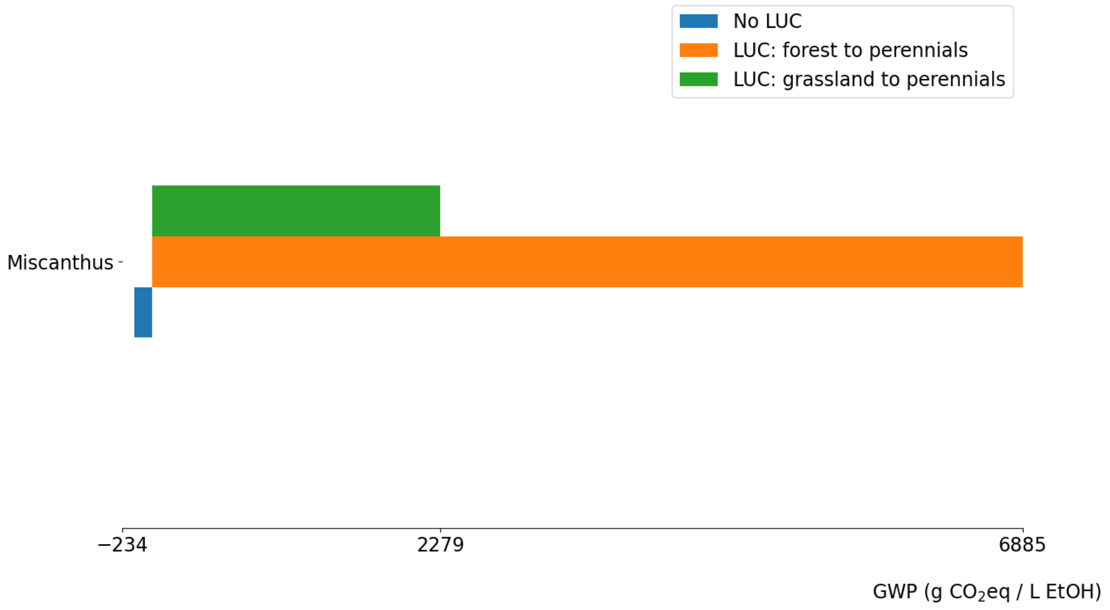


Figure 2.6: Comparison of GWP between two different LUC scenarios for miscanthus-to-ethanol production and gasoline, expressed in g CO_2eq per MJ of fuel.

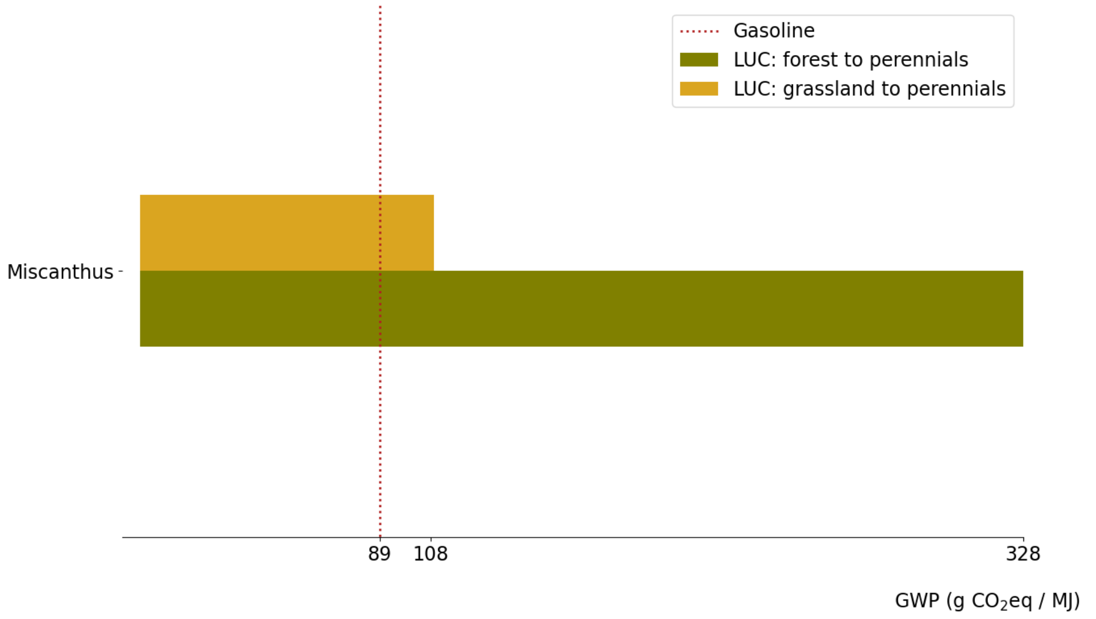
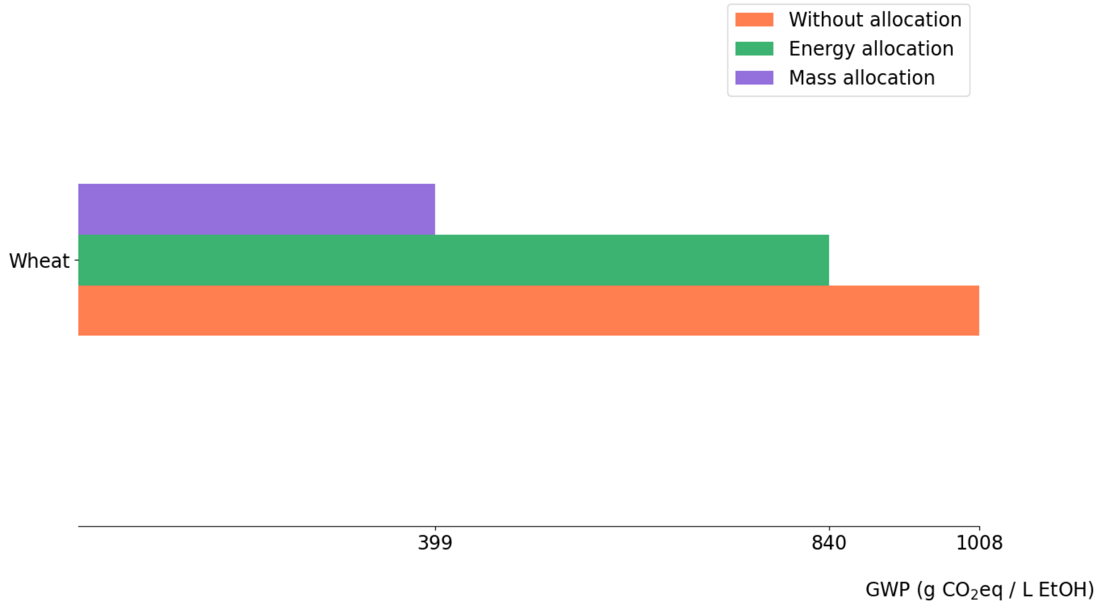


Figure 2.7: Comparison between global warming potential of wheat-based bioethanol for different consideration of the co-products: no allocation, energy allocation, and mass allocation. Adapted from Belboom *et al.* (2015).



use of one allocation method over another has a significant influence on the attributed global warming potential. This is illustrated in **Figure 2.7** for wheat-based bioethanol production in Belgium.

Belboom *et al.* (2015) estimated the global warming potential associated to the production of bioethanol from wheat, considering all steps of the production chain taking place in Belgium (i.e. cultivation of wheat, transportation from field to plant, and wheat transformation). In their assessment, it is specified that the production of 1000L of bioethanol from wheat, results in the co-production of 46.9 kg of gluten and 1158 kg of liquid feed. The global warming potential reported in their paper are based on a comparison between no allocation, resulting in 1008 g CO_2eq (L EtOH)$^{-1}$, and energy allocation, resulting in 840 g CO_2eq (L EtOH)$^{-1}$. Based on their data, an additional mass allocation was performed in this work and resulted in a value of 399 g CO_2eq (L EtOH)$^{-1}$. These different GWP impacts are compared in **Figure 2.7**.

From this case, it can be concluded that allocation methods have a significant influence on the assessment of global warming potential related to bioethanol production as a mass allocation results in a global warming potential that is less than half the one obtained using an energy allocation. In fact, such variations in global warming potential due to different allocation methods can be observed in numerous LCAs and allocation is seen as one of the main controversial issues. As demonstrated, an allocation by mass can result in the majority of impacts being allocated to the co-products rather than the bioethanol which is the main (economic) product. Economic allocation could evolve over time due to fluctuations in prices over time.

2.3 EROI

The EROI of first-generation ethanol is well documented in the literature for European countries. Thus, results for wheat- and sugar beet-based bioethanol are founded on an in-depth review of articles published on the web. This isn't the case for bioethanol produced from miscanthus and forest residue, as studies on the EROI of bioethanol produced from these feedstocks remain scarce or not relevant due to their geographical location. As a result, a computation of the EROI for these two bioethanol production routes was performed.

Table 2.5 reports the range of EROI values for the four bioethanol production scenarios under consideration in this work. The trend is for second-generation bioethanols to achieve higher EROI values than first-generation bioethanols. This is in part due to lower inputs in cultivation and harvesting, in particular for forest residue which do not require to invest in a cultivation process, as it is assumed that forest residue is a waste and energy requirements start from the harvesting stage. This remains true for miscanthus whose cultivation process is less energy-intensive than wheat and beet crops.

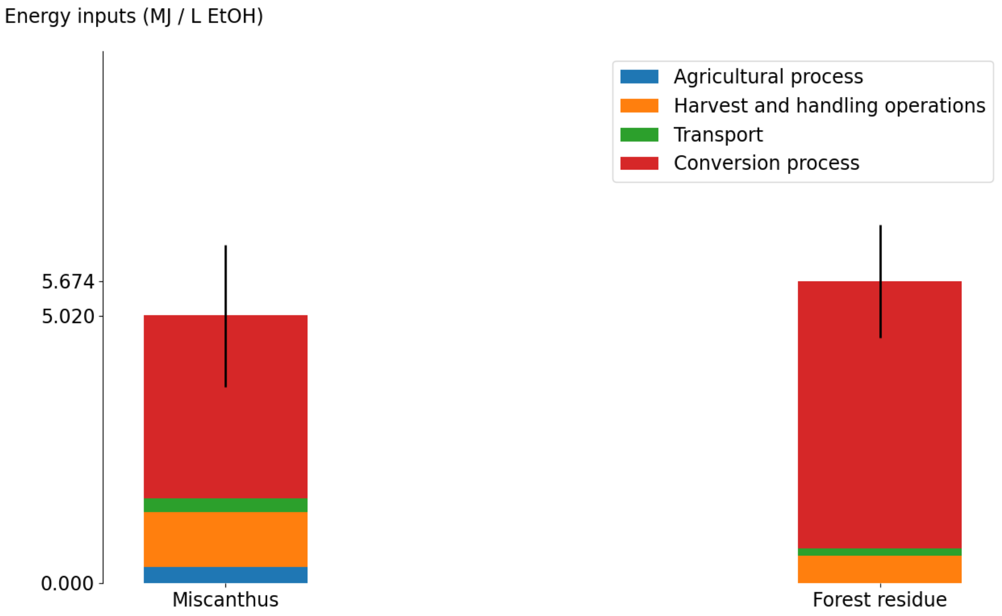
Table 2.5: EROI of bioethanol: estimates from wheat-, sugar beet-, miscanthus-, and forest residue-to-ethanol.

Feedstock	EROI	Sources
Wheat	0.69:1 - 2.72:1	ADEME *et al.*(2002) ; Elsayed *et al.* (2003) ; Woods and Bauen (2003) ; Sourie *et al.* (2005)
Sugar beet	1.28:1 - 2.21:1	ADEME *et al.*(2002) ; Elsayed *et al.* (2003) ; Woods and Bauen (2003) ; Sourie *et al.* (2005)
Miscanthus	3.31:1 - 5.69:1	Calculated in this work [a]
Forest residue	3.12:1 - 4.56:1	Calculated in this work [a]

[a] See details in **Appendix B**.

The EROI of bioethanol produced from second-generation feedstocks, i.e. miscanthus and forest residue, was computed considering system boundaries from "cradle-to-gate". This includes feedstock cultivation (when relevant), collection, transportation to the plant, and conversion into ethanol. **Figure 2.8** compares the energy inputs for each step of the production chain between miscanthus- and forest residue-based bioethanol. As expected, no contribution to feedstock cultivation is associated to forest residue. In

Figure 2.8: Comparison of energy inputs between miscanthus- and forest residue-to-ethanol production. Inputs expressed in MJ (L EtOH)$^{-1}$.



addition, it can be observed that forest residue requires less energy for harvest and transport operations. However, conversion process for forest residue to bioethanol appears to be more energy-intensive than conversion of miscanthus into bioethanol. On average, both raw materials have energy inputs of the same order. Variations indicated with the black vertical lines on the graph accounts for fluctuations in possible conversion yields and energy input entries. Further details on the energy inputs needed for the production of bioethanol using these two feedstocks can be found in **Annex B**.

2.4 LCOF

In order to account for significant differences in processes resulting in different cost breakdown among the bioethanol production scenarios, a starch-based, a sugar-based, and a cellulosic bioethanol plants are considered. The starch-based plant is considered for the conversion of wheat, the sugar-based for the conversion of sugar beet, and the cellulosic plant for the conversion of miscanthus and forest residue.

Table 2.6 reports the main parameters assumed for the three bioethanol plants under consideration. The design and construction time is assumed to take three years. Two additional years are considered for the cellulosic plant to achieve full production capacity. This ramp-up time varies from one project to another, due in particular to different pretreatment techniques applied on different feedstocks. Here, to facilitate the computation it is assumed that the ramp-up phase is the same for miscanthus and forest residue, although not necessarily true depending on the pretreatments considered. Moreover, no ramp-up phase is assumed for conventional bioethanol plants (i.e. starch-based and sugar-based). A medium-scale bioethanol plant of 50 million liters bioethanol production is assumed for each of the three plants. Another important parameter is the discount rate r, set to 10% according to previous design reports and based on the recommendation in Short *et al.* (1995).

Table 2.6: Assumption on the main parameters used for the three bioethanol plant models.

Parameter	Value		Sources
Design and construction time	3 years		Zhao *et al.* (2015) ; Peters *et al.* (2015) ; Pavlenko (2018) ; Pavelenko *et al.* (2019) ; Pavlenko and Searle (2019) ; Lim *et al.* (2022)
Plant ramp-up time	5 years		" "
Percentage of plant capacity during ramp-up phase [a]	Year 1	Year 2	" "
	50%	75%	
Lifetime	20 years		" "
Plant capacity	50 million liters bioethanol production per year		Own assumption [b]
Discount rate	10%		Peters *et al.* (2015) ; Humbird *et al.* (2011) ; Lim *et al.* (2022)

[a] No ramp-up phase assumed for conventional bioethanol plants.

[b] Medium-scale bioethanol plant chosen to facilitate the computation of the LCOF for each bioethanol production scenario.

Capital expenditures (CAPEX) can be broken down into various components, including site development, construction, equipment purchases and installation, and other costs. Equipment costs reflect the size for which it was designed. Costs aren't computed over for each item, instead a scaling exponent is used to account for the difference in equipment size between projects. The basic following formula is used:

$$\text{considered cost} = \text{original cost} \times \left(\frac{\text{considered size}}{\text{original size}}\right)^n \tag{2.4}$$

where $n = 0.7$ taken from Humbird *et al.* (2011). An exponential factor of 0.6 to 0.7

is often cited in the literature. Moreover, as projects discussed in the literature were developed several years ago, equipment costs collected are adjusted using the Chemical Engineering Plant Cost Index (CEPCI) (Chemical Engineering, 2023). The formula used to compute these adjustments is the following:

$$\text{2023 cost} = \text{base cost} \times \left(\frac{\text{2023 CEPCI}}{\text{base CEPCI}}\right) \tag{2.5}$$

Changes in currencies are further applied in order to express prices in € as most prices found are given in US \$. It must be noted that CAPEX are considered to be the same for the production of bioethanol from miscanthus and forest residue as the same cellulosic bioethanol plant is considered for both feedstock.

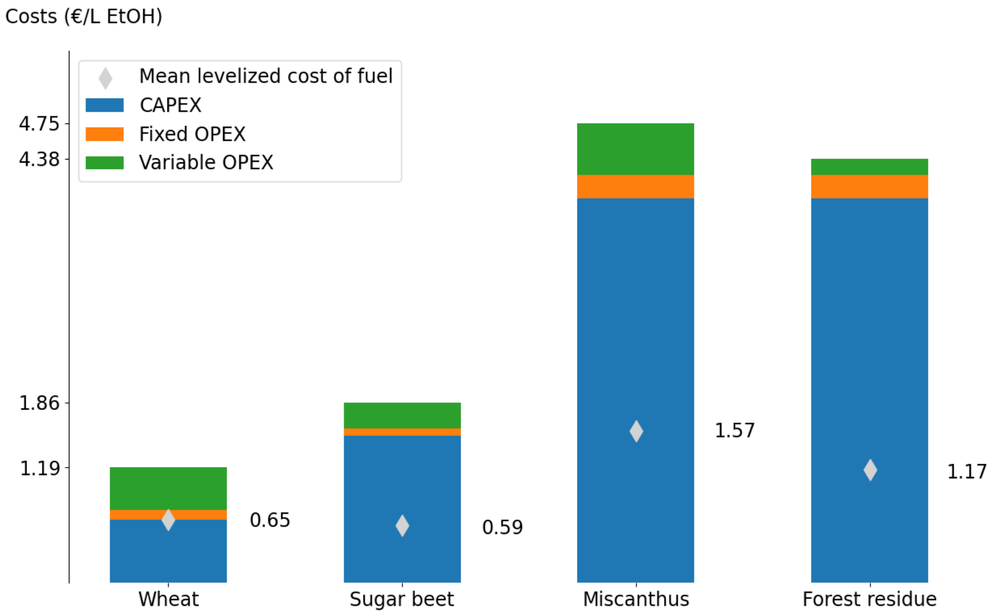
Operational cost (**OPEX**) consists of fixed operational costs (**Fixed OPEX**) of labor and maintenance and the variable operational costs (**Variable OPEX**) of feedstock and material inputs. As most studies reported Fixed OPEX in the United States of America (USA), salaries are downscaled to account for labor cost difference with Belgium. Labor burden is assumed to be 90% of the salaries according to Humbird *et al.* (2011). The latter article is used to estimate maintenance and other unspecified expenditures. As for CAPEX, Fixed OPEX are considered to be the same for the production of bioethanol from miscanthus and forest residue.

In contrast to Fixed OPEX, Variable OPEX varies according to the annual amount of bioethanol produced. This encompasses feedstock costs alongside additional inputs such as water and energy. Feedstock costs used are farmgate prices. This model doesn't include feedstock loading and transportation costs. Moreover, feedstock costs depend on the amount of feedstock consumed, estimated based on the feedstock's specific ethanol yield. Except for wheat, for which a unique ethanol yield of 434 L EtOH $(\text{ton})^{-1}$ was retained, various ethanol yields were reported resulting in variations of the LCOF obtained for the remaining other feedstocks.

The levelized cost of fuel calculated for each of the bioethanol scenarios are reported on **Figure 2.9**. It can be observed from the figure that the two first-generation bioethanols have a significant lower production cost than the two second-generation bioethanols. In particular, sugar beet as a feedstock for bioethanol production presents the lower levelized cost (average LCOF of 0.59 €/L EtOH). It is the miscanthus-based bioethanol which presents the most expensive scenario, with an average levelized cost of 1.57 € $(\text{L EtOH})^{-1}$.

Looking closer at **Figure 2.9**, CAPEX of second-generation bioethanols are much higher than for first-generation bioethanols. This trend is confirmed in the literature, with capital costs of advanced conversion technologies being typically much higher than for conventional bioethanols (Peters *et al.*, 2015). Within first-generation bioethanols, it can be noted that sugar beet results in a lower levelized cost than wheat, despite the fact that the total investment costs are higher for sugar beet. This is because the levelized cost is not that impacted by the capital costs on a lifetime of 20 years as considered, rather it is more influenced by the operational costs. It can be observed that the Variable

Figure 2.9: CAPEX, Fixed OPEX, and Variable OPEX expressed in € (L EtOH)$^{-1}$ and mean levelized cost of fuel for the four bioethanol production scenarios. Further details are available in **Appendix C**.



OPEX of sugar beet-based bioethanol is lower as compared to wheat-based bioethanol, due to a lower feedstock cost. Regarding second-generation bioethanols, it was assumed that both feedstock shared a same model of cellulosic bioethanol plants, thus sharing CAPEX and Fixed OPEX. However, Variable OPEX differ between both raw materials. Miscanthus appears to have a higher Variable OPEX driven by a higher feedstock costs, resulting in a higher levelized cost.

2.5 PA

In general, the public tends to express support for biofuels. Indeed, most of the studies focusing on European Union (EU) countries find an overall supportive attitude from the public towards biofuels. However, this global trend is sometimes challenged in some articles (Løkke *et al.*, 2021). The latter article claims that several factors can shape public's opinion on biofuels, including influence of the media and main discourses, the distribution of risks associated with the production of biofuels, and the limited knowledge of the public. A lack of knowledge is assumed to contribute to large uncertainties in public opinion and support towards biofuels, as opinions can change as additional knowledge and insights are gained. Moreover, the feedstock used for the production of bioethanol is find to be of importance when it comes to public opinion. First-generation bioethanol has in general a lower support than second-generation bioethanol, due in particular to the competition with food and perceived increase of food prices or shortages (Gaskell *et al.*, 2010). This provides an initial insight into the public's approval of the four raw materials under consideration.

Dragojlovic and Einsiedel (2015) investigated whether making people more aware of the possible negative effects of increasing second-generation bioethanol production could cause less public support for it. It concluded that effects of bringing additional information to the public regarding possible drawbacks of second-generation biofuels could lead to less public support. However, overall, second-generation such as energetic crops (e.g. miscanthus) and wood wastes obtained a good support from the public. As observed in the literature for EU countries, first-generation biofuels received a lower support (less than half of the people surveyed support edible biomass for biofuel production). The lower support for conventional biofuels are mainly due to the argument of an increase of food prices. Moreover, as the public's knowledge on biofuels is often limited, a part of the public associates bioethanol based on forest residue as a cause of deforestation. The argument put forward is that the use of this resource is an indirect consequence of the massive production of wood-based products. It is interesting to note that deforestation among the public is often associated to the effects of reduced habitats on biodiversity. While this statement isn't wrong, few people mention the induced GHG emissions related to deforestation, and thus the impact on global warming. The article stipulates that connecting deforestation with increase GHG emissions requires a relatively high level of scientific knowledge.

As a qualitative criterion used in the MCDA, an approach consisting in evaluating the support of the public towards the different bioethanol production scenarios into quantified data was performed. The method used is based on a likert-scale, assigning a score indicating the intensity of the support for each feedstock. The scale is reported in **Table 2.7**.

Table 2.7: Likert-scale for qualitative data.

Score	Support intensity
1	No support
2	Low support
3	Moderate support
4	High support
5	Unconditional support

To assess for uncertainties related to the public support of different bioethanol technologies, different scenarios are considered based on the information reported. The general results would indicate a high support of the public for both miscanthus and forest residue, while a low support would be assigned to first-generation bioethanol. A further scenario where the public would make a link between forest residue-based bioethanol and deforestation, would bring the support toward forest residue to a low support, on an equivalent level than conventional bioethanol. Such variation in public's perceptions on different feedstocks for bioethanol production will give an insight to how public opinion could influence decision-making processes. This influence will be conducted through a sensitivity analysis of the MCDA, presented in the following chapter.

Chapter 3

MCDA: results and discussion

This chapter aims to unveil the outcomes of the MCDA. The AHP as specified in **Chapter 1**, which can determine the relative importance of the criteria, is used to determine the weights of the three dimensions and those of the criteria in each dimension. The TOPSIS method is then used to rank the different bioethanol production scenarios according to the set of weights attributed to the criteria, and based on the results presented in **Chapter 2**.

The assignment of weights to criteria depends on a specific viewpoint, and in such decision-making processes stakeholders with different interests are involved. In order to take into account the possible preference of decision-makers for one set of criteria over others, several cases of weight allocation are examined:

1. Equal importance: assigning an equal weight of 0.20 to each of the five criteria (case 1).
2. One dominant dimension with the remaining of equal importance (cases 2 to 4). This means that a dominant weight is attributed to one of the three dimensions (i.e. whether to the environmental, techno-economic, or social dimension), and the two remaining dimensions share an equal weight. Within each of the dimension, the criteria have the same importance, meaning the same weight. Taking case 2 as an example, a dominant weight of 0.60 is attributed to the environmental aspect, and the two remaining aspects receive a weight of 0.20 each. The WF and GWP criteria obtain an equal weight of 0.30, while the EROI and LCOF criteria share an equal weight of 0.10. The public acceptance being the unique social criterion, it gets the weight attributed to the social aspect (i.e. 0.20).
3. For each of the cases 2 to 4, a sensitivity analysis is conducted. In case 2 and 3, the weights assigned to the dimensions remain the same, but changes in weight attribution within the dominant dimension is performed. Taking sub-case 2a as an example, within the environmental dimension, WF is given a weight of 0.67 and the remaining 0.33 are assigned to the GWP criterion. For case 4, modifications are made in the decision matrix to account for different scenarios of public acceptance as this criterion is much sensitive to numerous factors.

Table 3.1 shows the results obtained from the AHP-TOPSIS combined method for each of the cases studied. A dark bullet point indicates that the bioethanol production scenario is considered sustainable, while a blank circle indicates the opposite. A sustainable scenario is selected on the basis of its TOPSIS performance score. The alternative with the best score (i.e. the closest to 1) is considered sustainable. Other options with a performance score that differs from the highest within less than 5% are also considered sustainable.

Table 3.1: Results obtained from the AHP-TOPSIS combined procedure for each of the cases examined. A dark bullet indicates that the bioethanol production scenario is considered sustainable, while a blank circle indicates the opposite.

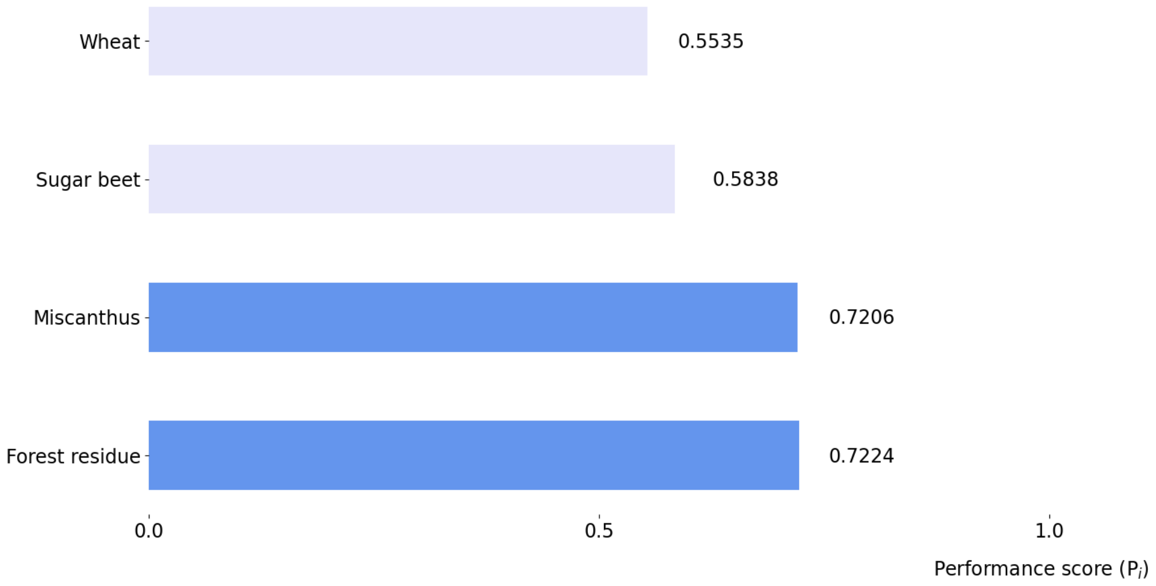
	Wheat	Sugar beet	Miscanthus	Forest residue
Case 1	○	○	●	●
Case 2	○	○	●	○
Sub-case 2a	○	○	●	○
Sub-case 2b	○	○	●	●
Case 3	○	○	○	●
Sub-case 3a	○	○	●	●
Sub-case 3b	●	●	○	○
Case 4	○	○	●	●
Sub-case 4a	○	○	●	○

Overall, the miscanthus-based bioethanol appears to be the most sustainable alternative. Indeed, in seven out of nine cases the miscanthus-based bioethanol is considered sustainable. Forest-residue as a feedstock for bioethanol production comes second with being considered sustainable in five out of the nine cases. In contrast, first-generation bioethanols (i.e. from wheat and sugar-beet) are considered sustainable once. In the subsequent sections, detailed investigation and interpretation are undertaken to further explore the results obtained for each case and sub-case examined.

1 Case 1

In this case, the AHP method is not used, as it is decided to impose an equal weight of 0.20 on each of the criteria. The performance scores obtained for all four bioethanol production scenarios are shown in **Figure 3.1**. It can be observed on this graph that both miscanthus and forest residue obtain a similar performance score of 0.72, ranking them as the sustainable solutions in this case. Meanwhile, first-generation bioethanols achieve a more modest score (0.55 for wheat and 0.58 for sugar beet). These results are obtained assuming that each criterion has equal importance, i.e. without favoring one or more criteria over the others. As a result, to interpret these scores, the overall performance of the four bioethanol production scenarios must be considered in relation

Figure 3.1: Performance scores obtained for case 1. The darker blue indicates that the alternative is considered sustainable, while the lighter blue indicates the opposite.



to the five criteria.

Looking at the big picture, second-generation bioethanols achieve better ratings on water footprint, global warming potential, energy return on investment, and public acceptance, compared to first-generation bioethanols. That's four criteria against one, where second-generation bioethanol achieve more favorable results. That being said, it is not quite true for the water footprint between sugar beet and miscanthus, as sugar beet has a lower impact. However the difference remains minimal, as it can be recalled that the water footprint of bioethanol produced from sugar beet varies between 243 and 903 L H_2O (L EtOH)$^{-1}$ while the water footprint of miscanthus-based bioethanol lies between 374 and 934 L H_2O (L EtOH)$^{-1}$.

In the event that a decision-maker does not decide whether one criterion is more or less important than another, and therefore assigns equal weight to each criterion, then miscanthus and forest residue would represent the most sustainable feedstocks for bioethanol production.

2 Case 2

The dominant dimension in this case is the environmental one. The weight distribution is reported in **Table 3.2**, and further details on the pairwise comparison matrix can be found in **Table D.1**. To outline the idea behind the weight assignment in this

Table 3.2: The overall weights of the criteria for case 2. For further details on the pairwise comparison matrix, see **Table D.1**.

Dimension /	Environmental	Techno-economic	Social	Weights
Criteria	0.60	0.20	0.20	
WF	0.5			0.30
GWP	0.5			0.30
EROI		0.5		0.10
LCOF		0.5		0.10
PA			1	0.20

case, the environmental dimension is given a dominant weight of 0.60 while the techno-economic and social dimensions share the remaining weights, i.e. 0.20 each. Moreover, criteria within the same dimension are considered to be of equal importance.

The results for case 2 are given on **Figure 3.2**. In this case, the miscanthus-based bioethanol gets the highest score (i.e. 0.86). Notice here that forest residue obtains a performance score of 0.77 which is higher than its own score in case 1, however, forest residue isn't considered here as sustainable. This is because each case is studied as an independent unit, as weight distribution differs from one case to another. Therefore, what is relevant here is to compare the performance scores according to a same weight allocation between the different bioethanol production routes. Furthermore, the term "sustainable" used here should be understood as sustainable in comparison to the other options.

The environmental impacts of miscanthus-based bioethanol as compared to the other feedstocks leads it to the highest score. For the other second-generation bioethanol under consideration, one could wonder how forest residue gets such a score while having the worst water footprint impact. Well, its poor performance in water footprint is perhaps balanced against a lower impact on global warming potential, achieving negative GWP values which translates a saving of GHG emissions. In addition, it should be borne in mind that the other criteria also come into their own, despite their lower weight, and that second-generation bioethanols have better overall performance as stated in case 1.

Once again, wheat and sugar beet as raw materials for the production of bioethanol are not getting the preference from decision-makers. Even sugar beet, which has the smallest water footprint relative to the other alternatives, receives an insufficient score of 0.67, far short of the 0.82 required to be considered sustainable in this case[1].

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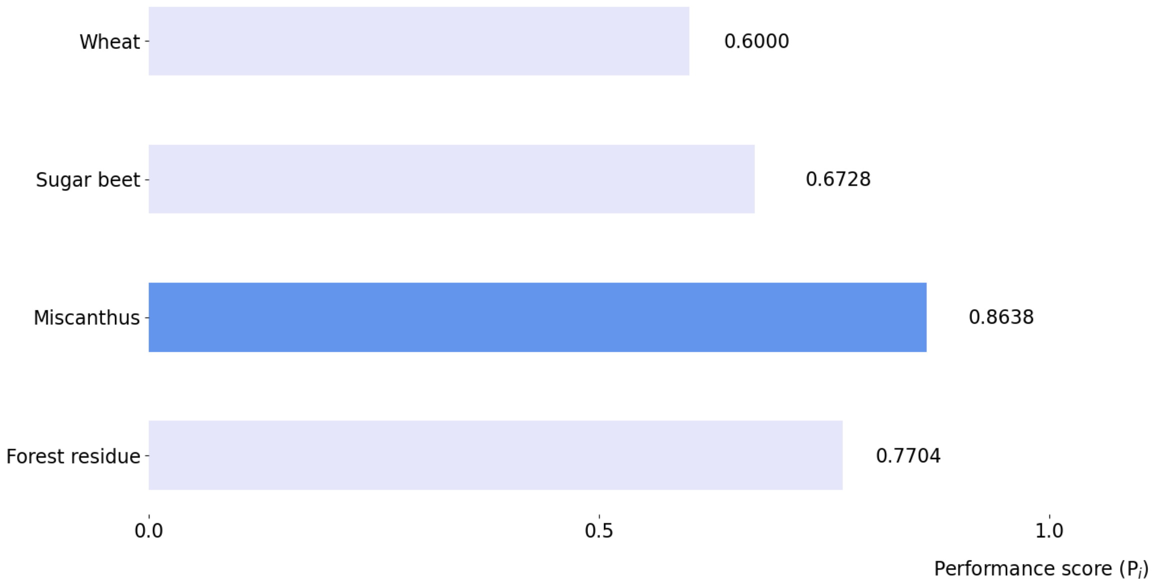
[1] Based on the condition stated in the introduction of this chapter. As a reminder, the condition states that an alternative can be considered sustainable without having the highest score if its score differs from the highest within less than 5%.

Figure 3.2: Performance scores obtained for case 2. The darker blue indicates that the alternative is considered sustainable, while the lighter blue indicates the opposite.



In what follows, it is proposed to investigate two additional sub-cases. In these sub-cases, the same weighting distribution for the dimensions is be maintained, with the environmental aspect dominating and its weight remaining at 0.60. The weights of the environmental criteria, however, are changed. In sub-case 2a, it is assumed that the water footprint criterion is more important than the global warming potential criterion. Likewise, it is assumed in sub-case 2b that the global warming potential criterion is more important than the water footprint criterion.

2.1 Sub-case 2a

The weight distribution for sub-case 2a is reported in **Table 3.3**. In this sub-case, the water footprint criterion is given a higher weight than the global warming potential criterion. This weight breakdown generates the results shown in **Figure 3.3**.

The miscanthus feedstock obtains the highest score (i.e. 0.88) and finds itself as the unique sustainable option in this sub-case. Miscanthus has a rather low water footprint, although sugar beet has an even lower impact. In fact, sugar beet comes second with a score of 0.76, however, miscanthus benefits from its good performance in the other indicators and retains its place as a sustainable solution. Wheat is the third feedstock with a score of 0.67 and it is the bioethanol produced from forest residue that gets the lowest score (i.e. 0.64). This disappointing score is explained to some extent from the fact that forest residue suffer from a high impact of water footprint. Its water foot-

Table 3.3: The overall weights of the criteria for sub-case 2a. The comparison matrix for the dimensions is the same as for case 2, i.e. **Table D.1**. For further details on the decision matrix of the environmental criteria, see **Table D.2**.

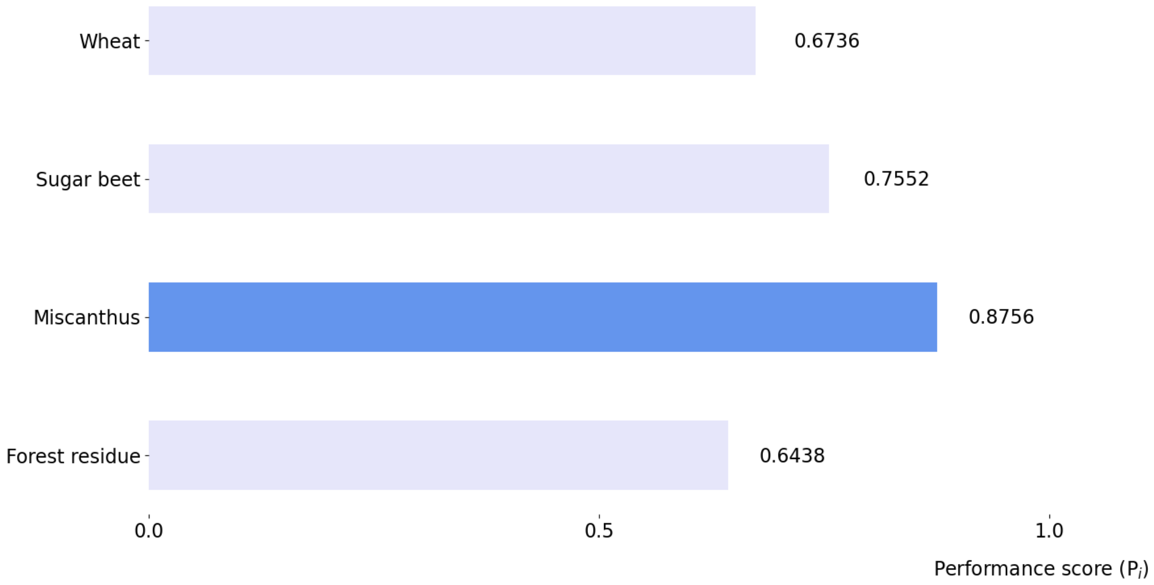
Dimension /	Environmental	Techno-economic	Social	Weights
Criteria	0.60	0.20	0.20	
WF	0.6667			0.40
GWP	0.3333			0.20
EROI		0.5		0.10
LCOF		0.5		0.10
PA			1	0.20

print was estimated in **Chapter 2** to range between 884 and 2720 L H_2O (L EtOH)$^{-1}$. Nonetheless, one might wonder how its footprint can be so large considering that it is a residual waste. The truth is that the relevance of this indicator is questionable, in particular for forest-based products as investigated in Launiainen *et al.* (2013). Their observation also applies in a certain sense to rain-fed agricultural products.

At present, the water footprint of rain-fed forest-based products consider the evapotranspiration (ET) as green water. When the sun warms the Earth's surface, water evaporates from both land and water bodies, while also being released from plants through transpiration, thus returning to the atmosphere. This phenomenon is referred to as evapotranspiration. ET is in fact the largest component of the water footprint of forest-based products (van Oel and Hoekstra, 2012). However, it is difficult to assess whether ET translates water utilization or consumption. On one hand, water utilization refers to flows from a given system or process that are made available for reuse. On the other hand, water consumption refers to water that is embedded in a product making it unavailable for further use. While ET can be perceived as water consumption when examined at a local scale, its perspective shifts when considered on a broader spatial (or extended temporal) scope. In this context, ET functions as a service to transport water vapor into the atmosphere and contributes to precipitation in other locations. From this perspective, ET can be seen as water utilization. Thus, defining ET as water consumption or utilization depends on the boundaries set to a given system. For this reason, Launiainen *et al.* (2013) suggest that ET should not be included in the water footprint of forest-based products as it fails in a local scale to consider water as a renewable and circulating source.

In the event where ET would have not been included in the water footprint of forest residue, the water footprint of that feedstock would have been much lower. This would have resulted in a much better performance score for bioethanol production from forest residue. Sub-case 2a therefore allows us to see which bioethanol would be the most sustainable in a context where the environmental aspect is given emphasis on a small scale. Thinking more in terms of large-scale and global environmental impact leads us

Figure 3.3: Performance scores obtained for sub-case 2a. The darker blue indicates that the alternative is considered sustainable, while the lighter blue indicates the opposite.



to consider sub-case 2b, where the focus in environmental aspects is on global warming potential.

2.2 Sub-case 2b

The weight distribution for sub-case 2b is given in **Table 3.4**. In this sub-case, the global warming potential criterion is given a higher weight than the water footprint criterion. This weight vector results in the performance scores shown in **Figure 3.4**.

Both miscanthus and forest residue outperforms the other bioethanol production scenarios with a score of 0.86. Thus, both alternatives are here considered sustainable. This isn't surprising when recalling the performances of these second-generation bioethanols when considering the global warming potential criterion. Indeed, miscanthus and forest residue offers possible negative global warming potential values, meaning that the production of bioethanol from these raw materials could lead to saving GHG emissions. Growing miscanthus often results in authors considering that it increases carbon stock in the land used while for forest residue it is assumed in several studies that residual lignin could be used to generate heat and power reinvested in the process, which would avoid using grid electricity and thus GHG emissions. The overall process would, using such assumptions, have a net-negative impact of the global warming potential of bioethanol production. However, one must remember that the estimated global warming potentials are highly sensitive to the assumptions made, system boundaries used, allocation meth-

Table 3.4: The overall weights of the criteria for sub-case 2b. The comparison matrix for the dimensions is the same as for case 2, i.e. **Table D.1**. For further details on the decision matrix of the environmental criteria, see **Table D.3**.

Dimension /	Environmental	Techno-economic	Social	Weights
Criteria	0.60	0.20	0.20	
WF	0.3333			0.20
GWP	0.6667			0.40
EROI		0.5		0.10
LCOF		0.5		0.10
PA			1	0.20

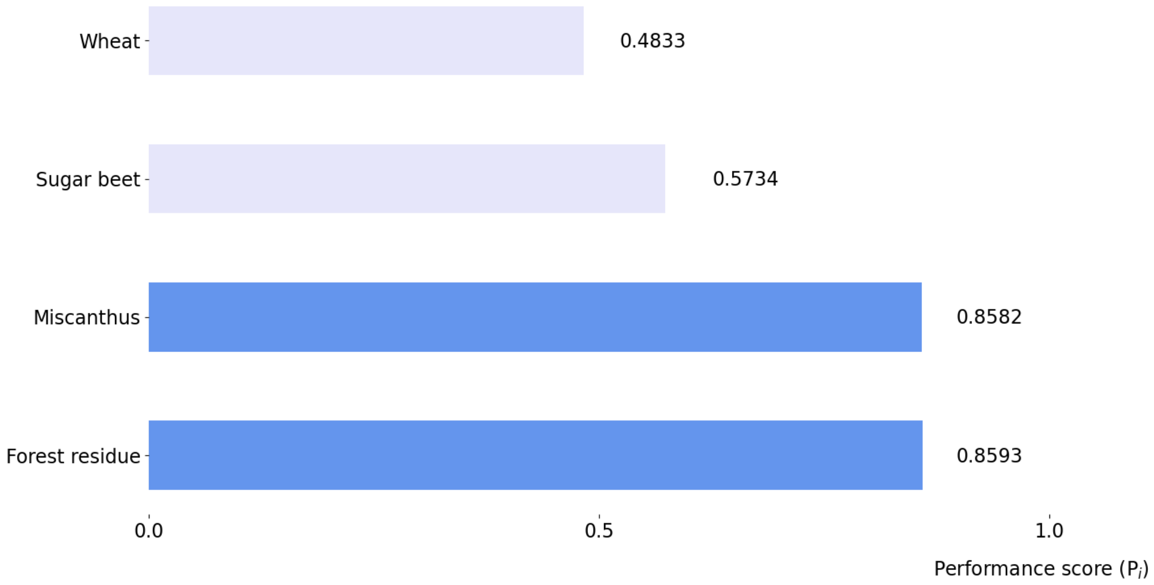
ods considered, and land use change.

In **Chapter 2**, it was demonstrated that land use change could increase the global warming potential of miscanthus-based bioethanol from -234 to 6885 g CO_2eq (L EtOH)$^{-1}$ when forest lands are converted into growing miscanthus (see **Figure 2.5**). Such a high global warming potential would exceed the emissions linked to fossil fuel use, and would contradict one of the arguments put forward for the use of bioethanol, which is to reduce emissions.

Global warming potential was also shown to be sensitive to different allocation methods as illustrated in **Figure 2.7**. To recap, Belboom *et al.* (2015) estimated the global warming potential of wheat-based bioethanol production in Belgium using no allocation which resulted in a global warming potential of 1008 g CO_2eq (L EtOH)$^{-1}$ and an energy allocation which resulted in a value of 840 g CO_2eq (L EtOH)$^{-1}$. A further mass allocation was performed in this work given the data from the latter article, and resulted in a global warming potential of 399 g CO_2eq (L EtOH)$^{-1}$.

That being said, even though miscanthus and forest residue present negative global warming potential values, caution must be taken when interpreting these results. Indeed, the reported values also indicate a maximum global warming potential of 1281 g CO_2eq (L EtOH)$^{-1}$ for bioethanol production from miscanthus. Likewise, an estimated global warming potential of 276 g CO_2eq (L EtOH)$^{-1}$ was reported for forest residue-based bioethanol. However, second-generation bioethanols still present lower global warming potentials than first-generation bioethanols with wheat-based bioethanol presenting a maximum reported value of 2545 g CO_2eq (L EtOH)$^{-1}$. This explains in some degree the reason for the low performance scores obtained for the two first-generation bioethanols considered (i.e. 0.48 for wheat-based bioethanol and 0.57 for sugar beet-based bioethanol). For further details on the reported global warming potential values, see **Appendix A**.

Figure 3.4: Performance scores obtained for sub-case 2b. The darker blue indicates that the alternative is considered sustainable, while the lighter blue indicates the opposite.



3 Case 3

The dominant dimension in this case is the techno-economic one. The weight distribution is reported in **Table 3.5**, and further details on the pairwise comparison matrix can be found in **Table D.4**. To outline the idea behind the weight assignment in this case, the techno-economic dimension is given a dominant weight of 0.60 while the environmental and social dimensions share the remaining weights, i.e. 0.20 each. Moreover, criteria within the same dimension are considered to be of equal importance.

The results for case 3 are shown on **Figure 3.5**. The outcome of the AHP-TOPSIS combined method in this case indicates forest residue as the most sustainable feedstock for bioethanol production (i.e. 0.64). Miscanthus-based bioethanol comes then second with a score of 0.58, falling short to be considered sustainable in this case. Nevertheless, it can be observed that the scores obtained are quiet low compared to the ones that result from the other cases.

The performance of second-generation bioethanols is also contrasted here, as both techno-economic criteria (i.e. energy return on investment and levelized cost of fuel) have a higher weight in the decision process, and both feedstock fails to perform in the levelized cost as compared to first-generation bioethanols. However, it can be recalled that both miscanthus and forest residue obtain maximum EROIs of 5.69:1 and 4.56:1, respectively, while wheat and sugar beet fail to even obtain maximum EROIs higher than

Table 3.5: The overall weights of the criteria for case 3. For further details on the pairwise comparison matrix, see **Table D.4**.

Dimension /	Environmental	Techno-economic	Social	Weights
Criteria	0.20	0.60	0.20	
WF	0.5			0.10
GWP	0.5			0.10
EROI		0.5		0.30
LCOF		0.5		0.30
PA			1	0.20

Figure 3.5: Performance scores obtained for case 3. The darker blue indicates that the alternative is considered sustainable, while the lighter blue indicates the opposite.

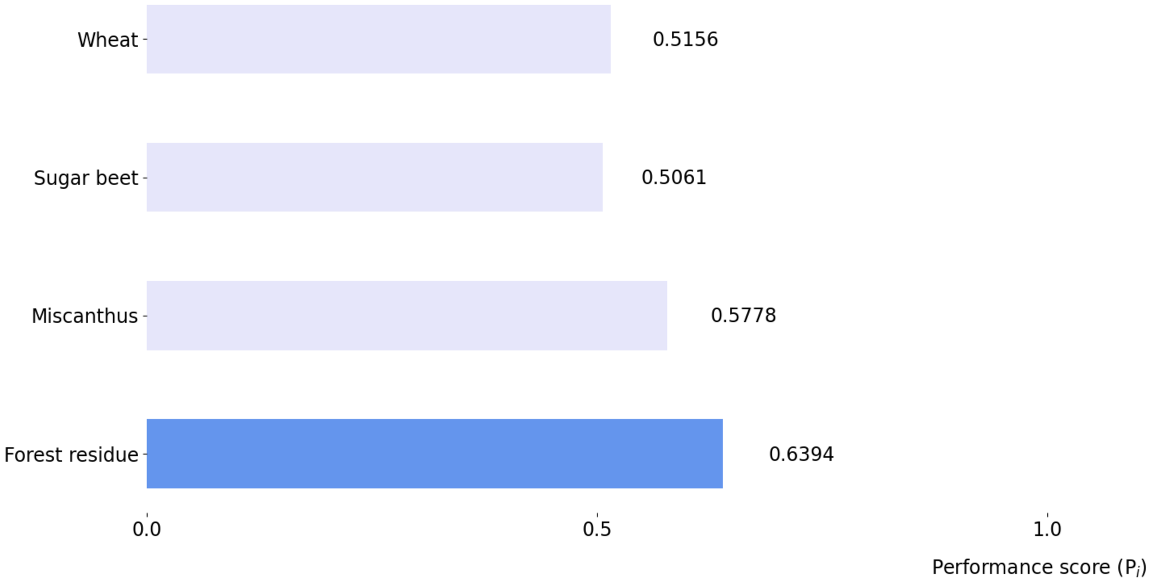


Table 3.6: The overall weights of the criteria for sub-case 3a. The comparison matrix for the dimensions is the same as for case 3, i.e. **Table D.4**. For further details on the decision matrix of the techno-economic criteria, see **Table D.5**.

Dimension /	Environmental	Techno-economic	Social	Weights
Criteria	0.20	0.60	0.20	
WF	0.5			0.10
GWP	0.5			0.10
EROI		0.3333		0.20
LCOF		0.6667		0.40
PA			1	0.20

the minimum observed for both second-generation bioethanols (recall **Table 2.5**). It is the sugar beet feedstock that results in the lowest score (i.e. 0.51) although it's the one that results in the lowest levelized cost.

Given the contrasting results for both first- and second-generation bioethanols in the two techno-economic criteria, it appears interesting to conduct a sensitivity analysis for these criteria. In what follows, it is proposed to investigate the outcome of the MCDA when keeping a same weight distribution for the three dimensions (i.e. the techno-economic aspect remains the dominant one with a weight of 0.60), but varying the weights of the criteria within the techno-economic dimension. In sub-case 3a, a higher weight is attributed to the levelized cost of fuel, while in sub-case 3b the energy return on investment is assigned a higher weight.

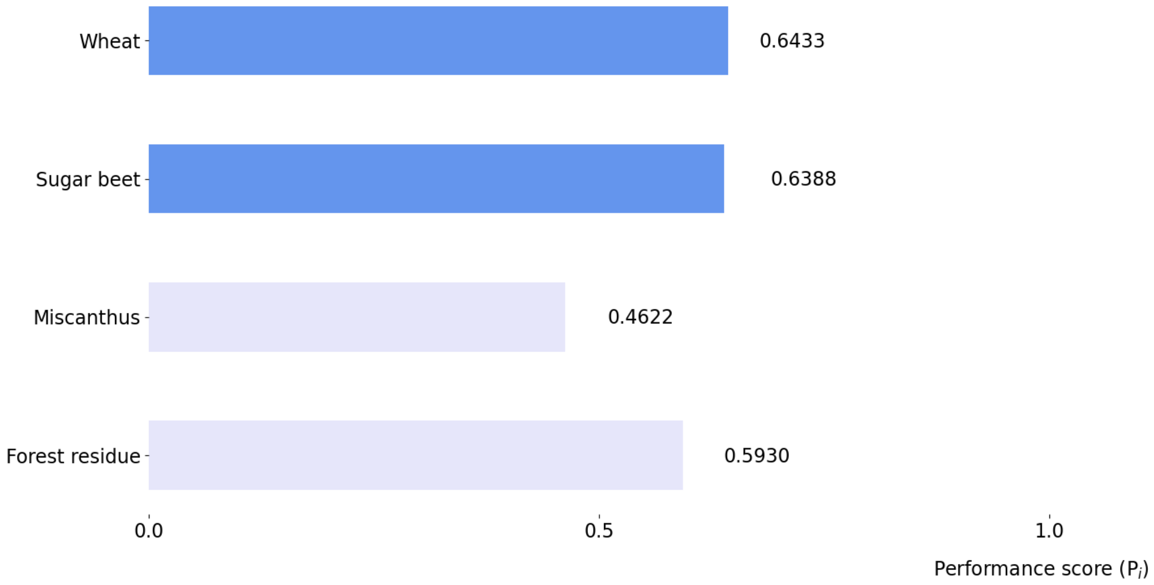
3.1 Sub-case 3a

The weight distribution for sub-case 3a is reported in **Table 3.6**. In this sub-case, the levelized cost of fuel criterion is given a higher weight than the energy return on investment criterion. This weight breakdown generates the results shown in **Figure 3.6**.

Both wheat and sugar beet as feedstock for bioethanol production are considered sustainable (both obtain a score of 0.64). This is the unique case where first-generation bioethanols are considered sustainable over second-generation bioethanols. The reason for this, is that although first-generation bioethanols underperform second-generation bioethanols in most of the criteria, it outperforms significantly enough miscanthus- and forest residue-based bioethanol to outcome as the sustainable alternatives. However, it must be noted that their performance score remains quiet low.

In **Chapter 2**, it was seen that bioethanol production using sugar beet was given the lowest levelized cost, estimated on average at 0.59 € (L EtOH)$^{-1}$. Then came second wheat-based bioethanol (LCOF = 0.65 € (L EtOH)$^{-1}$). About twice the cost of first-

Figure 3.6: Performance scores obtained for sub-case 3a. The darker blue indicates that the alternative is considered sustainable, while the lighter blue indicates the opposite.



generation bioethanols came bioethanol production from forest residue (LCOF = 1.17 € (L EtOH)$^{-1}$) and miscanthus-based bioethanol with an average estimated levelized cost of 1.57 € (L EtOH)$^{-1}$. These high levelized costs associated with the production of advanced bioethanol is a challenge for their development. In fact, it is widely recognized that the most significant challenge to the widespread adoption of cellulosic bioethanol is not technological but economic (Peters *et al.*, 2015). In particular, capital availability remains the biggest challenge to the large-scale commercialisation of second-generation bioethanol. As a reminder from the results obtained in the previous chapter, CAPEX for a cellulosic plant of 50 million bioethanol liters capacity was estimated at 198.45 million euros, while it was estimated at 75.81 millions euros for the sugar-based plant (i.e. for the conversion of sugar beet) and it was estimated at 32.73 million euros for the starch-based plant (i.e. for the conversion of wheat).

To a certain extent, the weight distribution in this sub-case reflects a reality in which the economic aspect is often given priority over other aspects. It is not surprising, then, that today's bioethanol consumption includes a large proportion of first-generation bioethanol, although recent policies are tending to encourage the production of cellulosic bioethanols over first-generation bioethanols.

Table 3.7: The overall weights of the criteria for sub-case 3a. The comparison matrix for the dimensions is the same as for case 3, i.e. **Table D.4**. For further details on the decision matrix of the techno-economic criteria, see **Table D.6**.

Dimension /	Environmental	Techno-economic	Social	Weights
Criteria	0.20	0.60	0.20	
WF	0.5			0.10
GWP	0.5			0.10
EROI		0.6667		0.40
LCOF		0.3333		0.20
PA			1	0.20

3.2 Sub-case 3b

The weight distribution for sub-case 3b is reported in **Table 3.7**. In this sub-case, the energy return on investment criterion is given a higher weight than the levelized cost of fuel criterion. This weight breakdown generates the results shown in **Figure 3.7**.

From **Figure 3.7**, one can observe that here again both miscanthus and forest residue results as the most sustainable feedstocks, with miscanthus reaching a higher score of 0.71 compared to the 0.68 obtained from forest residue. The difference between this sub-case and the previous sub-case is quiet impressive, with a shift from one case where the first-generation bioethanols were considered the most sustainable to a case where both wheat and sugar beet as feedstock to produce bioethanol obtain a low score of 0.38. As a reminder, miscanthus and forest residue have EROIs ranging from 3.12:1 to 5.69:1, respectively. In contrast, the reported EROIs for first-generation bioethanol varied between 0.69:1 and 2.72:1, thus not even reaching the lowest EROI obtained for second-generation bioethanol.

4 Case 4

The dominant dimension in this case is the social one. The weight distribution is reported in **Table 3.8**, and further details on the pairwise comparison matrix can be found in **Table D.7**. To outline the idea behind the weight assignment in this case, the social dimension is given a dominant weight of 0.60 while the environmental and techno-economic dimensions share the remaining weights, i.e. 0.20 each. Moreover, criteria within the same dimension are considered to be of equal importance.

The performance scores reported for this weight distribution are shown in **Figure 3.8**. Miscanthus- and forest residue-based bioethanol are identified as the sustainable solutions with score of 0.71 and 0.68, respectively. These results translate a stronger attitude from the public towards non-edible feedstocks for the production of bioethanol.

Figure 3.7: Performance scores obtained for sub-case 3b. The darker blue indicates that the alternative is considered sustainable, while the lighter blue indicates the opposite.

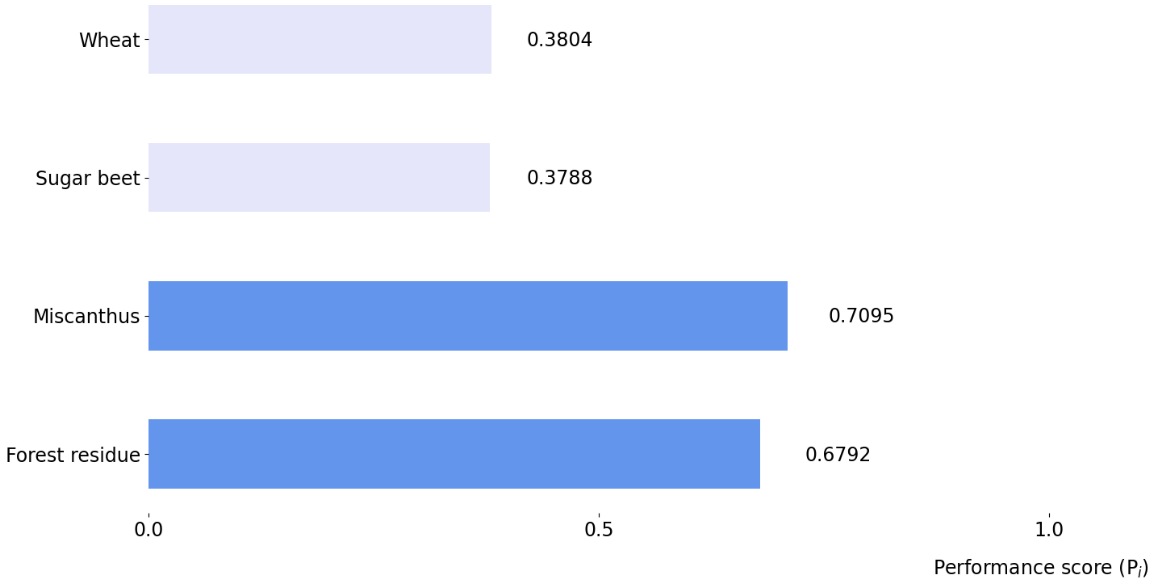
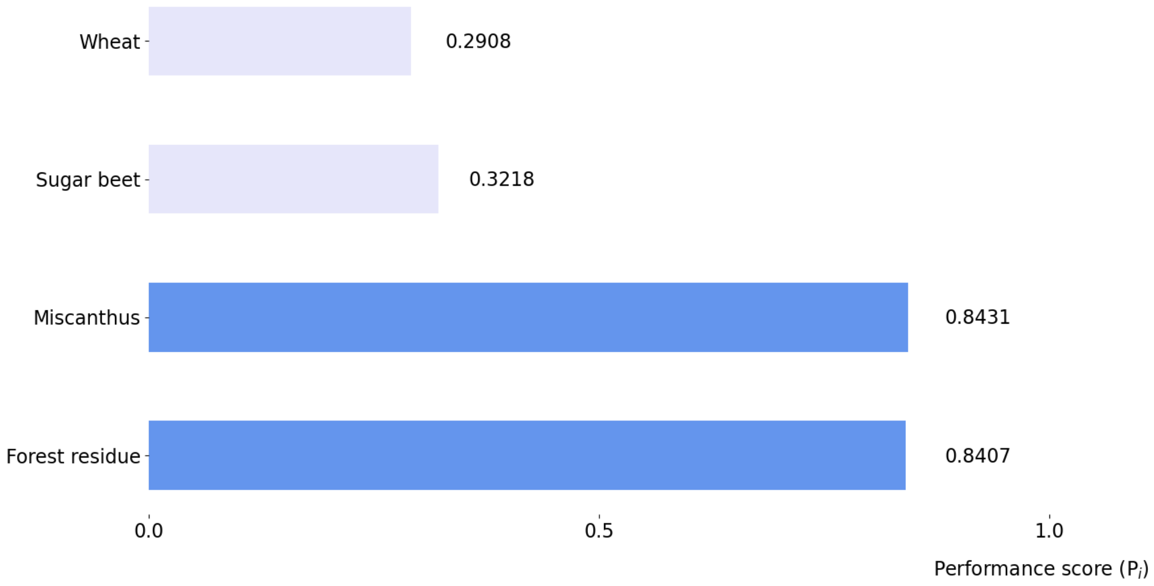


Table 3.8: The overall weights of the criteria for case 4. For further details on the pairwise comparison matrix, see **Table D.7**.

Dimension /	Environmental	Techno-economic	Social	Weights
Criteria	0.20	0.20	0.60	
WF	0.5			0.10
GWP	0.5			0.10
EROI		0.5		0.10
LCOF		0.5		0.10
PA			1	0.60

Figure 3.8: Performance scores obtained for case 4. The darker blue indicates that the alternative is considered sustainable, while the lighter blue indicates the opposite.



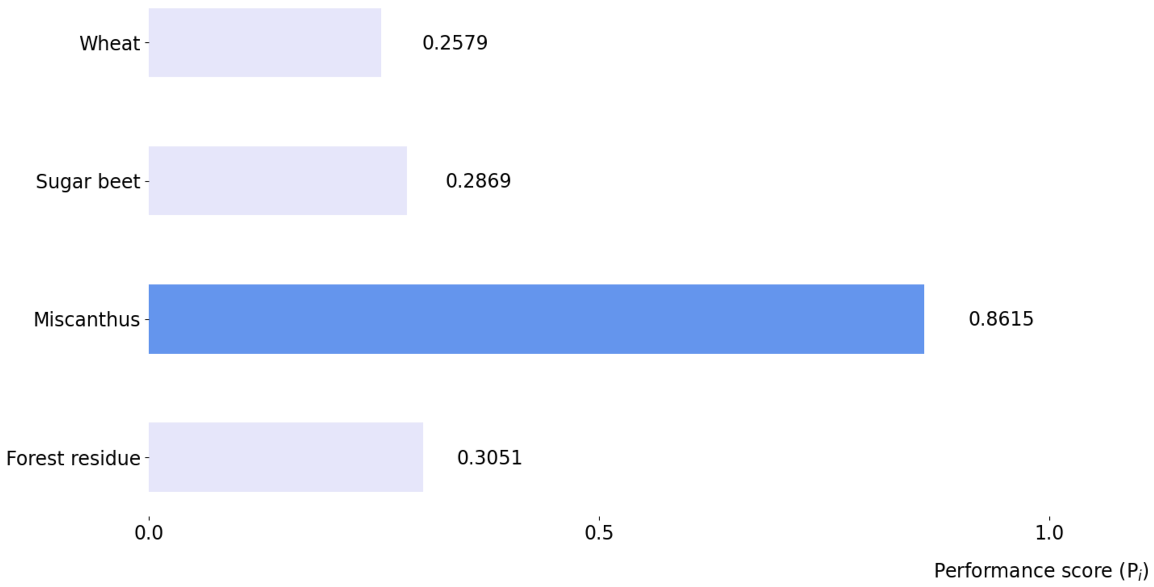
First-generation bioethanols suffer from the edible properties of the feedstocks used, associated to increase of the prices and food shortages from the public's opinion. This results in wheat-based bioethanol obtaining a performance score of 0.29, while sugar-beet performs not much better with a score of 0.32. An interesting pattern observed among public's opinion is linked to concerns of using wood waste as a feedstock for bioethanol production. The reasons for this skepticism are due to the concern that wood-based bioethanol could lead to increased logging, ultimately resulting in deforestation. As stated in the results of the public acceptance criterion, it is interesting to note that deforestation is more often a concern for the public due to concerns on the loss of biodiversity, rather than on increased GHG emissions. This is argued to be due to the fact that associating deforestation to global warming potential necessitates a certain level of scientific knowledge (Dragojlovic and Einsiedel, 2015).

4.1 Sub-case 4a

No changes in weight distribution as compared to case 4. In this sub-case, what is changed is the public's opinion on forest residue as a feedstock for bioethanol production. The support for this bioethanol option is considered here to be as low as for first-generation bioethanol. The results of the performance scores obtained are reported in **Table 3.9**.

This scenario indicates that miscanthus-based bioethanol outcomes as the unique sustainable bioethanol with a score of 0.86. Forest residue gets a poor score of 0.31.

Figure 3.9: Performance scores obtained for sub-case 4a. The darker blue indicates that the alternative is considered sustainable, while the lighter blue indicates the opposite.



Comparing these results with the results from case 4 suggests that public opinion could significantly influence the results of a decision-making process. However, it should be noted that the public acceptance is given here a weight of 0.60 which is quiet important.

Chapter 4

From a philosophical perspective

This chapter intends to draw a parallel with the master thesis of Guillaume Dos Santos, a student at the Faculty of Philosophy, Arts and Letters at UCLouvain, whose work is entitled “Le temps et le vivant - Esquisse de la temporalité du vivant végétal à partir de l’ontologie de la vie chez Hans Jonas”. Though our respective master theses are distinct from one another, a collaborative approach within an interdisciplinary framework has been pursued throughout the realization of this work. This was made possible thanks to the OIKOS initiative.

Note: *A special mention to Guillaume, without whom this chapter would not have been written. His contribution to the writing brought a philosophical perspective to the parallel that can be drawn between the use of biomass as an energetic vector and the temporality of plant life.*

1 Discussion

The concept of biomass, which - according to its scientific definition - means "the total mass of all living organisms measured in a population, an area or any other unit"[1] (Raven *et al.*, 2020) falls into the field of philosophically problematic categories, to the extent that it does not discriminate between what is living and what is dead: biomass designates both living organisms and dead matter. Biomass, then, is nothing other than that which has previously been stripped of its most essential characteristics - individuality, subjectivity, the form of life in question, etc. - in order to operate quantitative equivalences, in other words, to make one living or dead matter commensurable with another living or dead matter. Biomass reveals itself as a pure quantification of what is alive by the measure of what is dead.

Biomass thus fits into the framework of modern thought structured by the physical sciences, according to an ontology "whose model entity is pure matter, stripped of all the traits of life"[2] (Jonas, 2001). Biomass corresponds in effect to the category of extent

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[1] Translated from RAVEN, P., et al., Biologie, trad. de la 12ème éd. Américaine par P. L. Masson et C. Van Hove, Éditions De Boeck Supérieur, 2020, G-3

[2] Translated from JONAS, H., « La vie, la mort et le corps dans la théorie de l’être », in Le Phénomène de la vie. Vers une biologie philosophique, trad. D. Lories, Éditions De Boeck Université, 2001, p. 21.

defined by Descartes, applying to the field of bare materiality - *res extensa* - as opposed to the realm of *res cogitans*, applying to the thinking subject. Biomass thus totals a certain quantity of extended matter, whose specificity would be to consist of organic matter, stripped of all its life traits.

Distinguishing between the living and the inert requires us to place the concept within a temporality, i.e. a temporal horizon of transcendence open to a point of view, or a *point of life*. What distinguishes life from the "lifeless" is precisely the potentiality of "dying", which cannot constitute a threat to that which does not live. For *living matter*, this opens up a temporal horizon marked by the category of the future, synonymous for the living with the ever-imminent threat of death, in the face of which the living appears preoccupied with maintaining itself (Jonas, 2013).

As biomass used for energy production is mostly of plant origin, Guillaume's master thesis focused on characterizing the main features of the temporality of plant life. Such a temporality seems to be marked by its relationship to its environment (*hetero-temporality*), by the *growth* dynamism that drives it, and by its *iterability*, i.e. the cyclical form taken by the maintenance of its being in its relationship to the future (Marder, 2021).

Yet it seems that these three characteristics - hetero-temporality, growth temporality, *iterative* temporality - are not without interest for our own research.

Taking plant life into account - with a view to protecting the environment - also means taking its temporality into account. Its hetero-temporality makes plants particularly vulnerable to humans, who can take control of plant temporality, as is the case with cereal crops, but it also implies, in the opposite direction, an impact of plant temporality on the environment as a whole. Such control over plant time is therefore not without effect on the overall dynamics of the environments in which the plants controlled by man are rooted.

Plant iterability means taking into account the cyclical dynamics of plant time. Modifying a cycle is equivalent to transforming the overall dynamics of plant growth and, by extension, that of its environment.

Man's use of biomass for energy production therefore involves a series of co-adjustments with the plants that make up this biomass. For example, the dead organic matter that covers the forest floor, often made up of dead leaves and branches, feeds a whole trophic environment that depends on it (insects, fungi, bacteria, etc.) and which, by participating in the decomposition of this plant matter, helps to enrich the soil with oligo-elements that are then used for plant growth.

The distinction between dead and living organic matter thus seems partly inoperative, to the extent that dead matter becomes the support for new life. Through plant iterability, we see the idea of life after life, and a post-temporal temporality. Biomass converted into fuel could hypothetically fit into such a cycle, provided it ultimately benefits the living organism from which it is extracted. One way of looking at it would be to consider the usefulness of biofuels in the fight against global warming, which they would help - even if only slightly - to mitigate. Such a positive effect for living organisms, particularly plants, would in consequence make biofuels part of a positive cyclical dynamic that includes plant and human life in a kind of mutually beneficial ecosystem: in other words, a *symbiosis*.

Conclusion

A comparative assessment of four bioethanol feedstocks (i.e. wheat, sugar beet, miscanthus, and forest residue) was conducted in this work under a multi-criteria framework. The evaluation was based on five criteria derived from environmental, techno-economic, and social aspects (i.e. water footprint, global warming potential, energy return on investment, levelized cost of fuel, and public acceptance). A combined AHP-TOPSIS method was used to assign a relative importance to the criteria and rank the bioethanol alternatives according to the weight distribution. Eight different weight allocations were examined to account for different stakeholder's preferences. The findings of this work are resumed as follows:

- The miscanthus-based bioethanol shows up as a sustainable scenario in seven out of the nine cases. The bioethanol from forest residue comes second with five appearances as a sustainable option. Both first-generation bioethanols appear once as sustainable alternatives.
- Assigning an equal weight to each of the criteria results in both second-generation bioethanols being considered sustainable.
- When prioritizing the environmental criteria, miscanthus-based bioethanol is the most sustainable option. In this weight distribution, first-generation bioethanols suffer from poor performances in both environmental criteria as compared to second-generation bioethanols, while bioethanol from forest residue is affected as a result of a high water footprint. The relevance of the water footprint criterion for forest-based products is discussed. Assigning a higher weight to the water footprint criterion than to the global warming potential criterion results in the forest residue-based bioethanol getting the worst performance score. In contrast, switching the relative importance among the environmental criteria results in the bioethanol from forest residue appearing as a sustainable alternative.
- Giving a higher importance to the techno-economic aspect results in a higher score for bioethanol produced from forest residue. Among the techno-economic dimension, assigning a higher weight to the levelized cost of fuel criterion results in both wheat- and sugar beet-based bioethanol being considered as the sustainable alternatives. In this case, second-generation bioethanol obtain low scores due to a high levelized cost of production induced by important CAPEX, reaching about twice the levelized cost of first-generation bioethanol. However, favouring the energy return on investment criterion would switch these results and assess both second-generation bioethanols as sustainable. Indeed, miscanthus and forest residue as feedstocks for bioethanol production results in higher energy balances.

- Prioritizing the social aspect results in both second-generation bioethanols being considered sustainable. However, as public opinion is sensitive to a large number of factors and subject to instant change, a case where forest residue would be given a low support from the public is studied. This low support is due to its association to deforestation as perceived from the public, and results in forest-residue obtaining a poor performance score, letting miscanthus-based bioethanol as the unique sustainable option.

In addition to the MCDA conducted, the use of biomass for the production of bioethanol is discussed within a philosophical framework. This discussion takes shape with the contribution of a student from the Faculty of Philosophy, Arts and Letters at UCLouvain. This approach reflects the multi-dimensional nature of the challenges of transition and promotes further transdisciplinary collaboration.

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Appendices

Appendix A

Supplements - GWP

1 Wheat

Figure A.1: GWP of bioethanol produced from wheat. Details in **Table A.1**

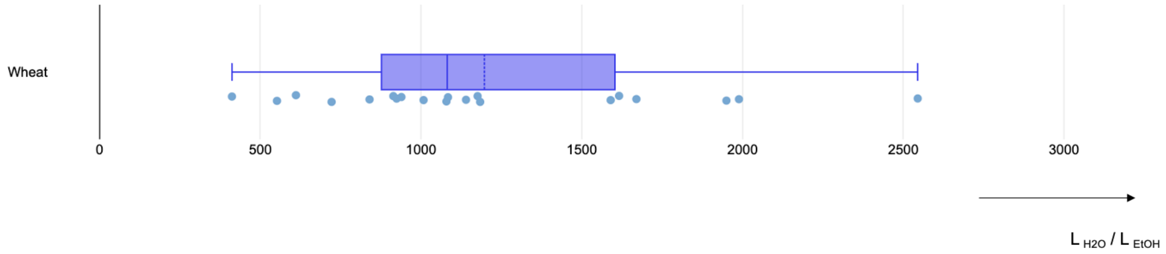

Table A.1: GWP associated with bioethanol production from wheat, expressed in g CO_2eq (L EtOH)$^{-1}$.

Region	GWP	Description	Sources
UK	611 ± 38	System boundaries: well-to-tank. Variations between minimum and maximum GWP due to uncertainties in the data used in all stages of the process. Allocation based on economic values for co-products.	Elsayed *et al.* (2003)
UK	1176 - 1616	System boundaries: well-to-tank. No co-product credits. Low and high estimates are due to different conversion efficiencies.	Woods and Bauen (2003)
BE	840 - 1008	System boundaries: well-to-tank. A GWP of 840 g CO_2eq (L EtOH)$^{-1}$ is obtained with energy allocation for co-products. The highest GWP is obtained without allocation.	Belboom *et al.* (2015)

FR	722	System boundaries: well-to-tank. System expansion is used for avoided impacts from recovered products. Co-products at each stage of the production are taken into account through mass allocation.	ADEME *et al.*(2002)
FR	1184	System boundaries: cradle-to-gate. Allocation based on economic values was performed.	Muñoz *et al.* (2013)
UK	1084	System boundaries: cradle-to-grave. Allocation based on economic values was performed.	Martinez *et al.* (2013)
UK	1140 - 1989	System boundaries: well-to-tank. This estimates are based on a basic configuration, i.e. heat is provided to the process in the form of steam generated from on onsite boiler using natural gas, and electricity is purchased from the grid. Low and high values are due to different allocation method: no allocation results in 1989 g CO_2eq (L EtOH)$^{-1}$; DDGS used as animal feed results in 1670 g CO_2eq (L EtOH)$^{-1}$; DDGS used as energy fuel results in 1140 g CO_2eq (L EtOH)$^{-1}$.	Punter *et al.* (2004)
UK	552 - 2545	System boundaries: well-to-tank. This estimates are based on a combined heat and power generation (CHP), i.e. Natural gas turbine for heat and electricity generation (CHP). Low and high values are due to different allocation method: no allocation results in 2545 g CO_2eq (L EtOH)$^{-1}$; DDGS used as animal feed results in 1079 g CO_2eq (L EtOH)$^{-1}$; DDGS used as energy fuel results in 552 g CO_2eq (L EtOH)$^{-1}$.	Punter *et al.* (2004)
UK	412 - 1590	System boundaries: well-to-tank. This estimates are based on a system expansion, i.e. straw boiler for heat and electricity generation from steam turbine. Low and high values are due to different allocation method: no allocation results in 1590 g CO_2eq (L EtOH)$^{-1}$; DDGS used as animal feed results in 939 g CO_2eq (L EtOH)$^{-1}$; DDGS used as energy fuel results in 412 g CO_2eq (L EtOH)$^{-1}$.	Punter *et al.* (2004)

SW	914	System boundaries: cradle-to-grave. Allocation based on economic values.	Martinez *et al.* (2013) from Bernesson *et al.* (2006)
UK	924	System boundaries: cradle-to-grave. Allocation based on economic values.	Martinez *et al.* (2013) from Rowe *et al.* (2009)
UK	1950	System boundaries: cradle-to-gate. Impacts shown for system expansion.	Falano *et al.* (2014)

2 Sugar beet

Figure A.2: GWP of bioethanol produced from sugar beet. Details in **Table A.2**

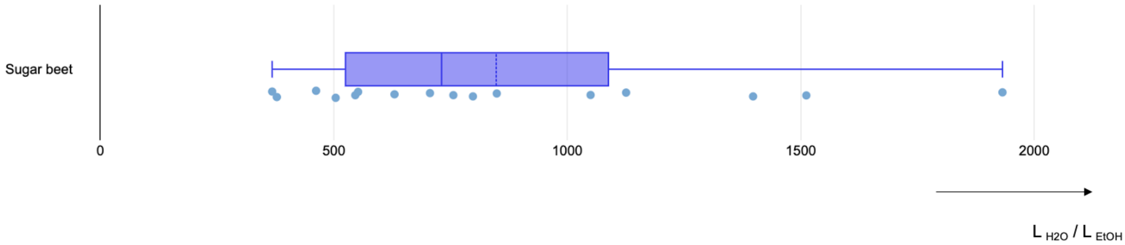

Table A.2: GWP associated with bioethanol production from sugar beet.

Region	GWP	Description	Sources
UK	849 ± 69	System boundaries: well-to-tank. Variations between minimum and maximum GWP due to uncertainties in the data used in all stages of the process. Allocation based on economic values for co-products.	Elsayed *et al.* (2003)
UK	1512 - 1932	System boundaries: well-to-tank. No co-product credits. Low and high estimates are due to different conversion efficiencies.	Woods and Bauen (2003)

FR	706	System boundaries: well-to-tank. System expansion is used for avoided impacts from recovered products. Co-products at each stage of the production are taken into account through mass allocation.	ADEME *et al.*(2002)
FR	552	System boundaries: cradle-to-gate. Allocation based on economic value was performed.	Muñoz *et al.* (2013)
UK	368	System boundaries: cradle-to-gate. Impacts shown for system expansion.	Falano *et al.* (2014)
FR	1126 - 1398	System boundaries: well-to-tank. Mass allocation was performed.	Chéron-Bessou *et al.* (2012)
GE	378 - 545	System boundaries: cradle-to-gate. In this process, sugar pulp (co-product of sugar beet-based bioethanol) is dried and used as animal feed. Different allocation methods are used (mass, energy, energy equivalents) along with system expansion as advised from the RED, which results in several values for GHG emissions expressed in g CO_2eq (L EtOH)$^{-1}$: 378, 462, 504, 546.	Weinberg and Kaltschmitt (2013)
GE	630 - 1050	System boundaries: cradle-to-gate. In this process, sugar pulp and vinasse (co-products of sugar beet-based bioethanol) produces biogas than can be burned in a CHP plant and used for heat and electricity production. Different allocation methods are used (mass, energy, energy equivalents) along with system expansion as advised from the RED, which results in several values for GHG emissions expressed in g CO_2eq (L EtOH)$^{-1}$: 630, 756, 798, 1050.	Weinberg and Kaltschmitt (2013)

3 Miscanthus

Figure A.3: GWP of bioethanol produced from miscanthus. Details in **Table A.3**

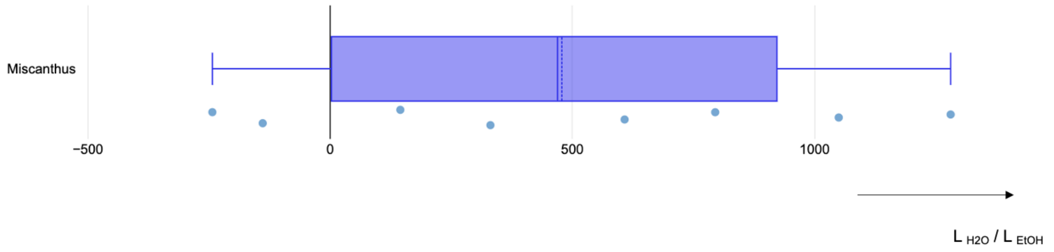

Table A.3: GWP associated with bioethanol production from miscanthus.

Region	GWP	Description	Sources
GE	608 - 1050	System boundaries: cradle-to-gate.	Lask *et al.* (2018)
UK	795 - 1281	System boundaries: cradle-to-gate.	Lask *et al.* (2018)
UK	-234	System boundaries: cradle-to-gate. Results shown for system expansion, with the system credited for production of butanol and propanol. Ethanol produced in a thermo-chemical refinery.	Jeswani *et al.* (2015)
UK	145	System boundaries: cradle-to-gate. Results based on economic allocation. Ethanol produced in a thermo-chemical refinery.	Jeswani *et al.* (2015)
UK	-139	System boundaries: cradle-to-gate. Results shown for system expansion, with the system credited for production of acetic and lactic acids, and electricity. Ethanol produced in a bio-chemical refinery.	Jeswani *et al.* (2015)
UK	331	System boundaries: cradle-to-gate. Results based on economic allocation. Ethanol produced in a bio-chemical refinery.	Jeswani *et al.* (2015)

4 Forest residue

Figure A.4: GWP of bioethanol produced from forest residue. Details in **Table A.4**.

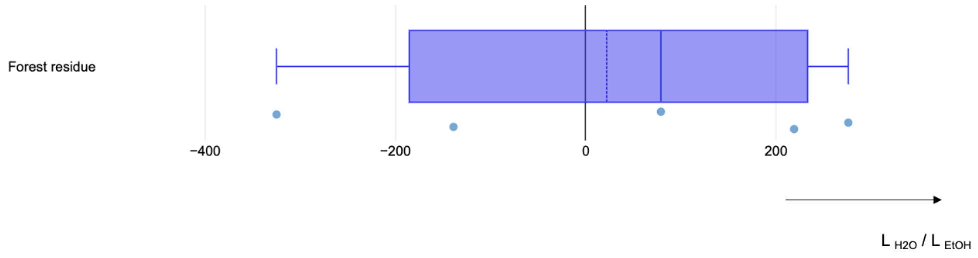

Table A.4: GWP associated with bioethanol production from forest residue.

Region	GWP	Description	Sources
UK	-325	System boundaries: cradle-to-gate. Results shown for system expansion, with the system credited for production of butanol and propanol. Ethanol produced in a thermo-chemical refinery.	Jeswani *et al.* (2015)
UK	79	System boundaries: cradle-to-gate. Results based on economic allocation. Ethanol produced in a thermo-chemical refinery.	Jeswani *et al.* (2015)
UK	-139	System boundaries: cradle-to-gate. Results shown for system expansion, with the system credited for production of acetic and lactic acids, and electricity. Ethanol produced in a bio-chemical refinery.	Jeswani *et al.* (2015)
UK	276	System boundaries: cradle-to-gate. Results based on economic allocation. Ethanol produced in a bio-chemical refinery.	Jeswani *et al.* (2015)
US	219 ± 5	System boundaries: cradle-to-gate.	Zupko (2019)

Appendix B

Supplements - EROI

1 Wheat

Table B.1: Reported EROI values for wheat-based bioethanol. Region where the estimations are computed are stated, along with the system description and the related source.

Region	EROI	Description	Sources
FR	2.04	System boundaries: well-to-tank. System expansion is used for avoided impacts from recovered products. Co-products at each stage of the production are taken into account through mass allocation.	ADEME *et al.*(2002)
UK	2.01 - 2.31	System boundaries: well-to-tank. Variations between minimum and maximum EROI due to uncertainties in the data used in all stages of the process. Allocation based on economic values for co-products.	Elsayed *et al.* (2003)
UK	0.69 - 2.72	System boundaries: well-to-tank. No co-product credits resulted in EROI ranging from 0.69 to 1.67. Using co-products (wheat straw) as fuel resulted in EROI ranging from 1.84 to 2.72. Low and high estimates are due to different conversion efficiencies.	Woods and Bauen (2003)
FR	1.19	System boundaries: well-to-wheel. Co-products are credited for their economic value (based on market prices in 2005).	Sourie *et al.* (2005)

2 Sugar beet

Table B.2: Reported EROI values for wheat-based bioethanol. Region where the estimations are computed are stated, along with the system description and the related source.

Region	EROI	Description	Sources
FR	2.05	System boundaries: well-to-tank. System expansion is used for avoided impacts from recovered products. Co-products at each stage of the production are taken into account through mass allocation.	ADEME *et al.*(2002)
UK	1.36 - 2.06	System boundaries: well-to-tank. No co-product credits resulted in EROI ranging from 1.36 to 1.61. Using co-products (pulp) as fuel resulted in EROI ranging from 1.43 to 2.06.	Woods and Bauen (2003)
FR	1.28	System boundaries: well-to-wheel. Co-products are credited for their economic value (based on market prices in 2005).	Sourie *et al.* (2005)
UK	1.85 - 2.21	System boundaries: well-to-tank. Variations between minimum and maximum EROI due to uncertainties in the data used in all stages of the process. Allocation based on economic values for co-products (i.e. sugar beet pulp).	Elsayed *et al.* (2003)

3 Miscanthus

Miscanthus is assumed to grow on marginal lands, which represents a total of 21000 acres in Belgium (Colla *et al.*, 2023). Based on the cited article, the potential yield is assumed to reach an average of 13.75 t DM $(\mathrm{ha})^{-1}$ $(\mathrm{year})^{-1}$, considering a LHV of miscanthus of 17.45 MJ $(\mathrm{kg})^{-1}$ (Dukiewicz *et al.*, 2014).

From Bullard and Metcalfe (2001), energy cultivation data inputs are retrieved for a lifespan of 20 years. With ethanol conversion yields of M. *x giganteus* summarized in **Table 2.4**, yields ranging from 2249 to 3870 L EtOH $(\mathrm{ha})^{-1}$ $(\mathrm{year})^{-1}$ are obtained.

An average distance of 50 km between harvesting site and ethanol plant is assumed, in accordance with Belboom *et al.* (2015). Miscanthus chips transportation is assumed to consume 0.91 MJ $(\mathrm{km})^{-1}$ $(\mathrm{ton})^{-1}$ (Hastings *et al.*, 2017).

Conversion process energy requirements are retrieved from Bansal *et al.* (2016).

Table B.3: Energy inputs for bioethanol production from miscanthus.

Inputs		Unit	Year of application	Sources		Unit
Rhizomes	4000	MJ/ha/year	1	Bullard and Metcalfe (2001)	0.05 - 0.09	MJ/L
Plantation (and previous soil preparation)	6331	MJ/ha/year	1	Bullard and Metcalfe (2001)	0.09 - 0.15	MJ/L
Weed control (herbicide and its applications)	1840	MJ/ha/year	1	Bullard and Metcalfe (2001)	0.03 - 0.04	MJ/L
Harvesting and handling operations	2939	MJ/ha/year	2 to 20	Bullard and Metcalfe (2001)	0,76 - 1.31	MJ/L
Removals	3680	MJ/ha/year	20	Bullard and Metcalfe (2001)	0.05 - 0.09	MJ/L
Transport	736.22	MJ/ha/year	2 to 20	Based on Belboom *et al.* (2015) ; Hastings *et al.* (2017)	0.19 - 0.33	MJ/L
Process	9776	MJ/ha/year	2 to 20	Bansal *et al.* (2016)	2.53 - 4.35	MJ/L
Total inputs					**3.69 - 6.35**	MJ/L

4 Forest residue

Table B.4: Energy inputs for bioethanol production from forest residue.

Inputs	Unit		Unit		Sources
Harvest	154.44	MJ/t DM	0.422 - 0.616	MJ/L	Based on Bonomi *et al.* (2019)
Transport	18.45	MJ/t DM	0.101 - 0.147	MJ/L	
Process					
Molasses	20.18	MJ/t DM	0.055 - 0.081	MJ/L	Based on Karlsson *et al.* (2014)
Enzyme product	823	MJ/t DM	2.247 - 3.284	MJ/L	Based on Karlsson *et al.* (2014)
Ammonia	412.56	MJ/t DM	1.126 - 1.646	MJ/L	Based on Karlsson *et al.* (2014)
Phosphorous	40.48	MJ/t DM	0.111 - 0.162	MJ/L	Based on Karlsson *et al.* (2014)
Sulphur	201.24	MJ/t DM	0.549 - 0.803	MJ/L	Based on Karlsson *et al.* (2014)
Total inputs	1531	MJ/t DM	4.610 - 6.738	MJ/L	

Conversion yields are considered to range between 0.13 and 0.19 kg DM (MJ EtOH)$^{-1}$ according to Karlsson *et al.* (2014) and Bonomi *et al.* (2019), respectively.

Harvest stage for forest residue are assumed to imply only the collection of the residues. Its energy input is considered to be 4.29 L Diesel (t DM)$^{-1}$ from Bonomi *et al.* (2019). For conversion of units, the energy content of diesel used is 36 MJ (L Diesel)$^{-1}$.

For the transportation, a truck with load capacity 40 t and a maximum load volume of 90 m^3 was assumed. It was assumed that the density of residues was 410 kg DM/ m^3 and that the truck consumed 39.2 L/100 km (Lindholm and Hansson, 2010). An average distance of 50 km is assumed between harvest location and bioethanol plant, as for miscanthus.

The conversion process inputs are derived from Karlsson *et al.* (2014).

Appendix C

Supplements - LCOF

1 Wheat

Table C.1: Total and per liter bioethanol capital cost, fixed operational cost, variable operational cost, and LCOF estimated in this work for wheat-based bioethanol.

		Wheat-based bioethanol	Sources
CAPEX	Total capital investment in million € (€ per liter capacity)	32.73 (0.65)	Based on McAloon *et al.* (2000)
Fixed OPEX	Total annual cost in million € (€ per liter bioethanol)	5.1 (0.10)	Based on McAloon *et al.* (2000)
Variable OPEX	Total annual cost in million € (€ per liter bioethanol)	21.96 (0.44)	Based on Hoekstra *et al.* (2011)
LCOF in € per liter bioethanol		0.65	

2 Sugar beet

Table C.2: Total and per liter bioethanol capital cost, fixed operational cost, variable operational cost, and LCOF estimated in this work for sugar beet-based bioethanol.

		Sugar beet-based bioethanol	Sources
CAPEX	Total capital investment in million € (€ per liter capacity)	75.81 (1.52)	Based on Haankuku *et al.* (2015) ; Bowen *et al.* (2010)
Fixed OPEX	Total annual cost in million € (€ per liter bioethanol)	3.21 (0.06)	Based on Haankuku *et al.* (2015) ; Bowen *et al.* (2010)
Variable OPEX	Total annual cost in million € (€ per liter bioethanol)	12.83 - 14.17 (0.26 - 0.28)	Based on Hoekstra *et al.* (2011) ; Foteinis *et al.* (2011) ; Weinberg and Kaltschmitt (2013)
LCOF in € per liter bioethanol		0.57 - 0.61	

3 Miscanthus

Table C.3: Total and per liter bioethanol capital cost, fixed operational cost, variable operational cost, and LCOF estimated in this work for miscanthus-based bioethanol.

		Miscanthus-based bioethanol	Sources
CAPEX	Total capital investment in million € (€ per liter capacity)	198.45 (3.97)	Based on Humbird *et al.* (2011)
Fixed OPEX	Total annual cost in million € (€ per liter bioethanol)	12.05 (0.24)	Based on Humbird *et al.* (2011)
Variable OPEX	Total annual cost in million € (€ per liter bioethanol)	19.74 - 33.98 (0.39 - 0.68)	Based on Khullar *et al.* (2012) ; Cerazy-Waliszewska *et al.* (2019) ; Turner *et al.* (2021)
LCOF in € per liter bioethanol		1.41 - 1.72	

4 Forest residue

Table C.4: Total and per liter bioethanol capital cost, fixed operational cost, variable operational cost, and LCOF estimated in this work for forest residue-based bioethanol.

		Miscanthus-based bioethanol	Sources
CAPEX	Total capital investment in million € (€ per liter capacity)	198.45 (3.97)	Based on Humbird *et al.* (2011) ;
Fixed OPEX	Total annual cost in million € (€ per liter bioethanol)	12.05 (0.24)	Based on Humbird *et al.* (2011)
Variable OPEX	Total annual cost in million € (€ per liter bioethanol)	6.82 - 9.98 (0.14 - 0.20)	Based on Bonomi *et al.* (2019) ; Karlsson *et al.* (2014)
LCOF in € per liter bioethanol		1.13 - 1.20	

Appendix D

Pairwise comparison matrices

Table D.1: Pairwise comparison matrix used for the computation of the dimension weights of case 2. Criteria within the same dimension are considered of equal importance.

	Environmental	Techno-economic	Social
Environmental	1	3	3
Techno-economic	1/3	1	1
Social	1/3	1	1

$\lambda_{\text{max}} = 3$; CI $= 0$; CR $= 0 < 0.1$

Table D.2: Pairwise comparison matrix used for the computation of the environmental criteria weights of sub-case 2a.

Environmental dimension	Water footprint	Global warming potential
Water footprint	1	2
Global warming potential	1/2	1

Table D.3: Pairwise comparison matrix used for the computation of the environmental criteria weights of sub-case 2b.

Environmental dimension	Water footprint	Global warming potential
Water footprint	1	1/2
Global warming potential	2	1

Table D.4: Pairwise comparison matrix used for the computation of the dimension weights of case 3. Criteria within the same dimension are considered of equal importance.

	Environmental	Techno-economic	Social
Environmental	1	1/3	1
Techno-economic	3	1	3
Social	1	1/3	1

$\lambda_{\text{max}} = 3$; $\text{CI} = 0$; $\text{CR} = 0 < 0.1$

Table D.5: Pairwise comparison matrix used for the computation of the techno-economic criteria weights of sub-case 3a.

Techno-economic dimension	Levelized cost of fuel	Energy return on investment
Levelized cost of fuel	1	2
Energy return on investment	1/2	1

Table D.6: Pairwise comparison matrix used for the computation of the techno-economic criteria weights of sub-case 3b.

Techno-economic dimension	Levelized cost of fuel	Energy return on investment
Levelized cost of fuel	1	1/2
Energy return on investment	2	1

Table D.7: Pairwise comparison matrix used for the computation of the dimension weights of case 4. Criteria within the same dimension are considered of equal importance.

	Environmental	Techno-economic	Social
Environmental	1	1	1/3
Techno-economic	1	1	1/3
Social	3	3	1

$\lambda_{\text{max}} = 3$; $\text{CI} = 0$; $\text{CR} = 0 < 0.1$

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