Sustainable biomass supply chain optimization-
Bioethanol and bio-electricity production

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Abstract

The transport sector, with its high consumption of fossil fuels, stands as a good sector for energy improvements through the introduction of alternative and sustainable energy sources, by means of electric cars and biofuel vehicles. Multi-period and spatially explicit features are embodied in a Mixed Integer Linear Programming framework to optimize a multi-echelon supply chain simultaneously in terms of economic (Net Present Value) and environmental performance (Greenhouse Gases emissions), considering biomass cultivation, transport, conversion into bioethanol or bioelectricity, distribution and final usage in alternative vehicles. Bioethanol and bioelectricity supply chains will be assessed considering corn, stover, Arundo Donax, Miscanthus, Poplar and wood residues as possible biomass feedstock to multiple first and second generation conversion technologies. Primarily, the environmental analysis will be done based on the emissions related to all the Life Cycle Assessment stages of the operation, and also by measuring the environmental impacts under different assessment methodologies to understand how the SC structure is affected by different impact evaluation methods. Results show the effectiveness of the model at providing decision makers with a quantitative analysis to optimize the economic and environmental performance of different design configurations, and it was verified that the method used to assess the environmental impacts affects not only the economic performance, but also the SC configuration.

Key words: Biomass supply chain, bio-power, bioethanol, optimization, sustainability

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1. Introduction

Energy demand has been steadily increasing for the past years, and it is still based on fossil fuels, which represent 80% of primary energy sources [1, 2]. This situation is particularly dramatic in the transport sector. One way to decrease the usage of petroleum-based fuels in the transport sector is by replacing them with biofuels or bioelectricity used by electric vehicles.

By focusing here on supply chain (SC) design and optimization, mathematical programming approaches have been exploited to analyze and optimize several biofuel SCs [3, 4].

Quite recently, d’Amore and Bezzo [5] developed a model for optimizing the SCs for ethanol and electricity production, both in terms of economic and environmental performances. In that study not only the upstream SCs for the production were considered, but also the final consumer needs were taken into account in the optimization. The SC was optimized considering only corn and stover as biomass feedstocks. However, further biomass types should be added to the model, so that more consistent conclusions regarding biomass SCs can be taken. Therefore this thesis, builds on the previous work considering a wider range of possible biomass sources such as Arundo Donax, Miscanthus, Poplar and forestry wood residues. These biomass types were chosen based on their good production yields and conversion efficiency ratios, and lower costs when compared to corn.

This thesis has two objectives: study the profitability and environmental impact of an energy SC that has bioethanol and bio-power as outputs, considering several different biomass feedstocks and conversion technologies; and to understand the influence of using different environmental impact assessment techniques on the SC design.

2. Assumptions and problem statement

The developed model is based on the one by d'Amore and Bezzo [5] representing the dynamic evolution of a bioethanol and bio-power SC located in North Italy, with the implementation of several new biomasses as feedstock options. The problem is formulated as a spatially explicit multi-period (over a 15-years' time horizon) and multi-echelon modelling framework, where a multi-objective optimization is executed, maximizing the economic performance (in terms of global NPV), while simultaneously minimizing of the environmental impact (in terms of overall GHG emissions). The geographical region addressed in this study, North Italy, was divided in 59 squares of 50 km of length, represented in the model by *g*, and one extra region (*g*=60) to represent the import of biomass, as it was proposed by Zamboni et al.[6].

The model was run for two different instances: in instance A the demand of both bioethanol and biopower are set, and in instance B a global energy demand is set, leaving to the solver to calculate the production rates of each product. In instance A, biopower demand was calculated based on an averaged EVs market share retrieved from d'Amore and Bezzo [5] of 3.26% by 2030 (*t*=5). The global ethanol demand comes as a percentage of the total gasoline demand at the demand centers, as it was defined by Zamboni et al. [6]. The global demand used in instance B is calculated by summing bioethanol and biopower demands that resulted from instance A.

Regarding biomass cultivation, the data for spatially specific yield for corn and stover was retrieved from Zamboni et al. [6] and Giarola et al. [7]. The cultivation yields of Arundo Donax, Miscanthus and Poplar were averaged from the values found in the literature [8 – 31], and then they were linked with the regions *g* according to the grid-dependent differential yields already described for corn and stover in [7]. In other words, although considering for each biomass *i* its respective yield (according to the different values found in the literature), the dependency of each yield on region *g* is assumed for each new biomass the same as for corn.

The availability of wood residues is related to timber production for each region. According to the literature [32 – 34] the yield of fresh biomass collected (moisture content of 60% (M60) when cut) is 0.299 ton of M60 per m^3 of timber. There is an average dry matter loss during drying and storage of 17% [35]. Thus the dry biomass average yield is 0.076 ton/m^3 timber. In order to find the biomass availability, it was necessary to retrieve the yearly timber production, for the regions of considered in the model [36]. It was considered that the woody biomass was only available at mountain regions.

For the biomass *i* unitary purchase costs ($UPC_{i,g}$) in each region *g*, the values for corn and stover were found in [6] and [7]. Data related to Arundo Donax, Miscanthus and Poplar was found in the literature [8, 12, 13, 16 – 18, 20, 21, 37 – 39] and an average of these values (UPC_i [€/ton]) was calculated. The purchase costs of wood chips, with a moisture content of 55% (M55) at the power plants, range from 29-38 [€/ton M55] [34]. These costs represent the price that is paid for wood chips at the power plants and are calculated on the entire wood residues SC. In the model, the biomass transport costs are optimized, and as a consequence transport costs should not be comprised in the wood chips purchase costs. Thus, transport costs, which represent 27.5% of the total costs [40], are discounted from the purchase costs of biomass. Considering all this information, the average biomass purchase cost with a moisture content of 55% is 24.26 [€/ton M55]. The correlation between dry and wet weight of the biomass becomes:

$$M = \frac{W_w - W_0}{W_w} * 100 \qquad (1)$$

where M is the moisture content and W_w and W_0 are the biomass wet and dry weights, respectively. The dry weight W_0 is 45% of W_w, consequently the average dry biomass purchase cost is 53.92 €/ton and is independent of region *g*.

In d'Amore and Bezzo [5], three conversion technologies were considered for bioethanol production but since the Integrated Grain-Stover Process technology was never selected in the SC optimization results, here only two technologies are taken into account, i.e. the Dry Grind Process (DGP), where only corn is converted into ethanol through a biological process (k=1), and the Ligno-Cellulosic Ethanol Process (LCEP), which does not use corn grains as a feedstock (k=2). The conversion efficiencies for ethanol production ($\gamma_{i,k}$ [ton eth/ton biomass]) through technology *k* for Arundo Donax and Miscanthus were taken from the literature [8 – 10].

Regarding electricity production, three technologies were considered: biomass direct combustion for Rankine steam cycle (k=11); biomass gasification for Turbo Gas cycle (k=22); and biomass gasification for Internal Combustion Engine (k=33). The conversion efficiencies for power production ($z_{i,k}$ [MWh/ton]) through technology *k* for the new biomasses *i* were obtained using the same methodology used in [5], i.e. by considering both the average efficiency of the Italian National grid (0.935) and the average conversion efficiency η_k for each technology *k* [8, 18, 34, 41 – 44].

The set of LCA stages *s* considered in the environmental evaluation is given by biomass growth, biomass pre-treatment, biomass transport, bioethanol production, biopower production, bioethanol transport, fuel distribution, bifuel vehicles usage, EVs usage, batteries production, and emission credits in terms of GHG saving. All the values for the emissions related to corn and stover growth, as well as the ones related to bioethanol transport and fuel distribution, were retrieved from d'Amore and Bezzo [5]. Regarding the new biomasses, the new mean values of emission factor for Arundo Donax, Miscanthus and Poplar production and usage were found in the literature [12, 16, 18, 30]. The mean value for the emissions related to forest wood residues was calculated considering only the emissions concerning the collection of the residues and the wood chipping processes. The fuel consumption of the processing machines and their respective CO_2 equivalent emissions were found in the literature [45, 46]. The mean values for emissions related to collection and chipping were calculated considering an average distance to the road side of 200 m [40] (Table 2). The emission factors related to biomass pre-treatment for the new biomasses were calculated following the same assumptions made by Giarola et al. [7]. Biomass transport emissions were considered the same as for corn and stover, for the new biomasses. The emissions from ethanol production and transport were calculated following the methodology used by Giarola et al. [7], and the ones related to electricity production also followed the methodology proposed for stover in that paper, but weighting each new biomass for its respective LHV. Finally, the emissions related to the end user and emission credits were estimated as in [5].

For the second part of the problem five different methods (*ReCiPe, Ecological Scarcity 2013, EDIP 2003, EPS 2000* and *Impact 2002+*) to assess the environmental impact of the SC will be applied, in order to see if the utilization different methods has influence on the economic performance and the SC structure. The data for the environmental impacts was based on a single score rate obtained in the software *SimaPro 8.2.3.0*. The modifications on the model and the implementation of the impacts were developed in this thesis.

3. Model formulation

The general modelling framework was formulated as a MILP problem according to the mathematical features outlined in Giarola et al. [7] and d'Amore and Bezzo [5].

In this multi-objective model, the first objective function is the maximization of the *NPV* [€], which is expressed as a minimization of its negative form:

$$Obj_{eco} = -NPV \tag{2}$$

The *NPV* is calculated by summing the SC profit (NPV_{chain} [€]) and the cost difference for the end user in driving EVs instead of bifuel vehicles ((NPV_{car} [€]):

$$NPV = NPV_{\ Chain} + NPV_{\ Car} \tag{3}$$

NPV_{chain} is calculated by summing up the discounted cumulative cash flows (*CCF* [€]) and subtracting the necessary capital investment to establish the production facilities (*FCC* [€]) and NPV_{car} is calculated by summing up the savings in driving electric instead of bifuel vehicles (*RISP* [€]) and subtracting the extra costs associated to buying the EVs (*exCO* [€]):

$$NPV_{chain} = CCF - FCC \tag{4}$$

$$NPV_{car} = RISP - exCO \tag{5}$$

The purpose of the second objective function is to minimize the total GHG impact (*TGHG* [kg of CO_2-eq]) that results from the SC operation:

$$Obj_{env} = TGHG \tag{6}$$

TGHG is calculated by summing up the total impacts (TI_t [kg of CO_2-eq/time period]) that result from the SC operation and the vehicle utilization by the end user:

$$TGHG = \sum_t TI_t \tag{7}$$

CCF and *FCC* are calculated as follows:

$$CCF = \sum_t CF_t \cdot dfCF_t \tag{8}$$

$$FCC = \sum_t TCI_t \cdot dfTCI_t \tag{9}$$

Where CF_t [€] is the cash flow and TCI_t [€] is the total capital investment for each time period. $dtCF_t$ and $dtTCI_t$ are the time dependent discount factors, which are calculated as shown in Giarola et al. [7]. TCI_t is calculated as in d'Amore and Bezzo [21], and CF_t comes from:

$$CF_t = PBT_t + D_t - TAX_t \tag{10}$$

Where D_t [€/time period] and TAX_t [€/time period], respectively depreciation charge and tax amount for each time period are calculated as in Giarola et al. [7] PBT_t [€/time period] stands for the profit before taxes and comes from:

$$PBT_t = Inc_t - VarC_t - FixC_t - D_t \tag{11}$$

Where Inc_t [€/time period] is the incomes, $FixC_t$ [€/time period] (calculated as in Giarola et al.

[7]) and $VarC_t$ [€/time period] represent the fixed and the variable costs.

The business incomes are calculated as follows:

$$Inc_t = \sum_{j,k,g} P^{TOT}_{j,k,g,t} \cdot MP_j \qquad (12)$$

Where $P^{TOT}_{j,k,g,t}$ [ton/time period or MWh/time period] is the production rate of product j converted through technology k in region g at time period t, and MP_j is the market price of product j.

Variable costs are calculated from:

$$VarC_t = EPC_t + BPC_t + PPC_t + TCb_t + TCf_t \qquad (13)$$

Where EPC_t [€/ton] represents ethanol production costs, BPC_t [€/ton] stands for biomass production costs, TCb_t [€/ton] and TCf_t [€/ton] represent biomass and ethanol transport costs, all these values are calculated as in Giarola et al. [7] PPC_t [€/tee] represents the electricity generation costs and is calculated as in d'Amore and Bezzo [5]. Where EPC_t [€/ton] represents ethanol production costs, BPC_t [€/ton] stands for biomass production costs, TCb_t [€/ton] and TCf_t [€/ton] represent biomass and ethanol transport costs, all these values are calculated as in Giarola et al. [7] PPC_t [€/tee] represents the electricity generation costs and is calculated as in d'Amore and Bezzo [5].

All the values related to NPV_{car} are calculated as shown by d'Amore and Bezzo [5].

Details about biomass pre-treatment and biomass transport can be found in Giarola et al [7]. The values related to biomass cultivation are also calculated following the work by Giarola et al. [7], with exception to biomass availability, which is now calculated from:

$$BA_{g,i} = GS_g \cdot BY_{i,g} \cdot AD_g \cdot BCD^{max}_g + BYwood_{i,g} \qquad (14)$$

The difference from the original formulation is the addition of $BYwood_{i,g}$ [ton/time period], which represents the yield of recovered wood residues, that does not depend on the agronomic-related factors like the other biomasses, since it is not a crop, but a residue from another activity.

Details about ethanol and power production can be found in Giarola et al. [7] and d'Amore and Bezzo [5], respectively. Ethanol ($Pf_{i,k,g,t}$ [ton/time period]) and power ($Pp_{i,k,g,t}$ [MWh/time period]) generation from biomass i, through technology k, in region g at time t are calculated with:

$$Pf_{i,k,g,t} = P^{T}_{'ethanol'} \cdot \beta_{i,k} \qquad (15)$$

$$Pp_{i,k,g,t} = ELtot_{k,g,t} \cdot \beta_{i,k} \qquad (16)$$

Where in the original model the parameter $\beta_{i,k}$ sets the type of biomass to be used in each technology, *a priori*, leaving to the model only the decision of which technology to use. In this new approach that would not be possible, since more than two biomass types are available. To get around this problem, the set of technologies k is divided for each technology, according to the number of biomass types that technology can use as an input. Originally, the technologies were defined by k={1, 2, 11, 22, 33}, in this new formulation they are defined as k={1, 2a, 2b, 2c, 2d, 2e, 11a, 11b, 11c, 11d, 11e, 22a, 22b, 22c, 22d, 22e, 33a, 33b, 33c, 33d, 33e} where all the possible combinations between technologies and biomass types are considered. The numbers represent the conversion technologies (as in the original model) and the letters (a, b, c, d, e) represent the biomass type (stover, Arundo Donax, Miscanthus, Poplar and wood, respectively). Then, $\beta_{i,k}$ is set as 1 when the biomass corresponds to the supposed technology and as 0 when that does not happen. This way the model is allowed to decide the combination between biomass types and technologies to be used.

Details about demand evolution and the environmental optimization can be found in d'Amore and Bezzo [5].

4. Model results

Supply chain optimization

The first objective of this thesis is to study the profitability and environmental impact of an energy SC that has bioethanol and bio-power as outputs, considering several different biomass feedstocks and conversion technologies. The model was run for optimizing both performances, considering a fixed ethanol and power demand (instance A) and a global energy demand leaving the output rates as a decision variable (instance B). The inclusion of new different biomass types as feedstock option in the model had a positive influence in the results, with an increase on the *NPV* of 6% to $6.67*10^8$€ and 3% to $1.77*10^9$€ on instances A and B, respectively, when compared to the original formulation. The main difference between the new and the original SC design is the use of Arundo Donax instead of stover to produce power.

In terms of SC configuration, for both instances the solution presented a mix between first generation biorefineries (k=1) for ethanol production from imported corn and gasification plants (k=22,33) for electricity generation from Arundo Donax. Although the values for NPV_{chain} of both instances are quite similar, the big difference in the *NPV* value is a consequence of the result for the NPV_{car}, which is much bigger in instance B, supported by a big EVs market share of about 12% at t=5 against the 3.26% of instance A. The downside of these configurations is their environmental performance. The total GHG emissions both for instance A and B are, respectively, 10% and 9% superior to the ones related to petrol (85.8 kg of CO_2/GJ) [47].

Regarding the environmental optimization, the addition of the new biomasses did not have any noticeable consequences on the performance. Even though one of these new biomasses is considered to be a residue from forestry activities, as it happened in the original model the preferred biomass for power production is still stover, which is also a residue. This happened because, since there is no fixed demand for power and ethanol, the production of ethanol was promoted by the solver in DGP (k=1) and LCEP (k=2) technologies, which bury fewer environmental impacts. Electricity production is only done in LCEP as a by-product. Although both instances present very good environmental performances with GHG emissions much lower than the ones associated to petrol, these configurations are unfeasible, given the fact that their *NPV* is negative. The operation of these systems would only be possible under a strong support policy, with governmental incentives of 3.35 €/GJ for instance A and 4.84 €/GJ for instance B, which adds up to a total of $1.17*10^9$ € and $1.70*10^9$ € over the 15 years, respectively.

Figures 1 and 2 present the SC configurations in the end of the time horizon, for both instances under both optimizations.

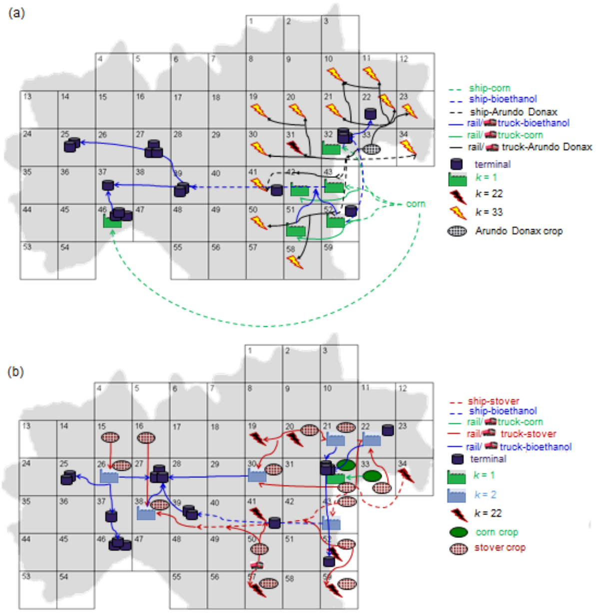

Figure 1 – SC configuration for instance A under economic (a) and environmental (b) optimization at *t*=5

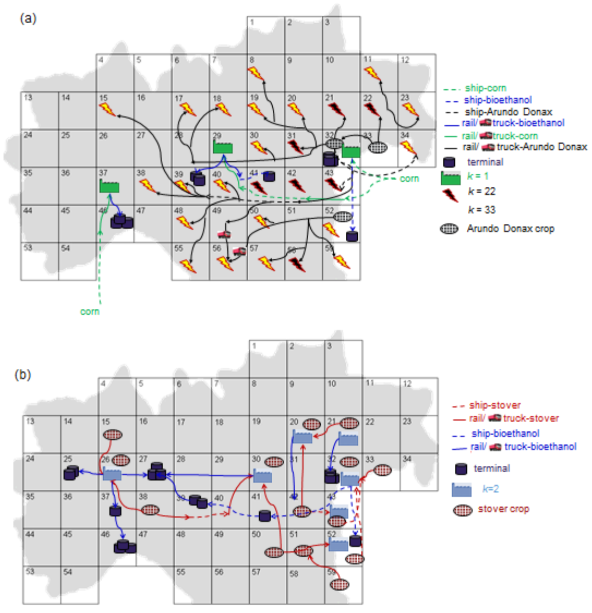

Figure 2 – SC configuration for instance B under economic (a) and environmental (b) optimization at *t*=5

Application of the different methods

The second goal of this thesis was to analyze the effect of using different methods to calculate the global environmental impact in the energy SC configuration and economic performance. The five methods (*ReCiPe, Ecological Scarcity 2013, EDIP 2003, EPS 2000* and *Impact 2002+*) were applied and the model was solved under environmental optimization for instance B. It was possible to conclude that the method chosen influences the decisions of the SCs design, since the configuration was different for each method and also different from the results from the main formulation, where

the environmental performance was analyzed only based on the total CO_2-eq emissions.

Figure 3 presents the number of plants for the five solutions obtained using the different methods, as well as the one obtained through the original formulation and already presented in the previous chapter, for comparison.

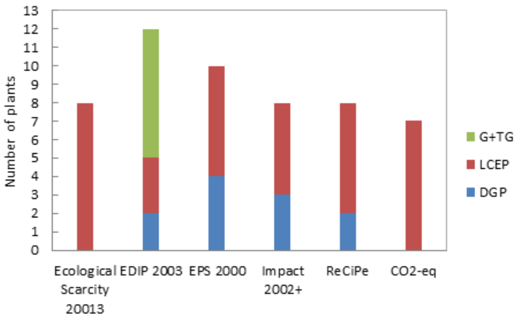

Figure 3 – Number of plants for the different methods

Not only is the number of plants and type of technologies used different between the solutions, but also the biomass types used as feedstock vary from method to method. In the solution from the original formulation only stover was chosen. With the implementation of the new methods other combinations of biomass were chosen: with *Ecological Scarcity 2013* only Miscanthus is part of the solution; with *EPS 2000* the biomasses used were corn, stover, and Miscanthus; for the remaining methods, corn, stover, Miscanthus and Arundo Donax were the chosen biomass types. Even though wood is considered a residue and therefore should account for fewer environmental impacts it is never used, as well as Poplar, mainly due to the fact that only in one case electricity production is considered.

However, the SCs structure is not the only issue affected by the implementation of the different methods. The economic performance also varies from method to method, as a consequence of the different SC designs. The differences in the economic performance go from $-2.31*10^9$ €, obtained using *Ecological Scarcity 2013*, to $-6.66*10^8$ €, using *EDIP 2003*. This variation of about $1.64*10^9$ € cannot be ignored by the decision makers of the SCs design.

The methods applied were not created in the same locations or in the same conditions and furthermore, the values used for the environmental impacts follow a different normalization process for each method. Having this in mind, the decision makers must be rigorous when selecting the environmental impact assessment method to be used, according to the purpose and scope of the project.

5. Conclusion

This thesis addressed two problems: the maximization of the economic performance and the minimization of the total environmental impacts of an energy SC to supply vehicles as a final market considering bioethanol and bio-power production in Northern Italy; and study the influence of choosing different environmental impact assessment methods in the SC structure. To assess these problems a MILP model based on the models previously developed by Zamboni et al. [1, 2], Giarola et al. [3] and d'Amore and Bezzo [4] was applied and implemented in GAMS®.

The problem comes as a consequence of the growing concern about the usage of fossil fuels, mainly in the transport sector, due to the depletion of reserves and mostly because of the environmental impacts associated. The model assesses the best way to supply energy for an alternative vehicles market, in order to be not only environmentally sustainable, but also economically competitive. The supply of energy can be done from ethanol or electricity, which can both be produced in multiple technologies and from a diverse set of biomass feedstock. The problem was studied from two perspectives: in instance A the ethanol and power demands are fixed, and in instance B there is a global energy demand defined, allowing the solver to adjust the production rates of ethanol and power.

The addition of Arundo Donax, Miscanthus, Poplar and wood residues from forestry activities in the model as biomass types as feedstock option had a positive influence in the economic performance, with an increase on the *NPV* of 6% and 3% on instances A and B, respectively, when compared to the original formulation. The main difference between the new and the original SC structure is the use of Arundo Donax instead of stover to produce power. In terms of SC configuration, for both instances the solution presented a mix between first generation biorefineries (k=1) for ethanol production and gasification plants (k=22,33) for electricity generation, which accounts for 16% of total energy produced in instance A and 40% in instance B . Although the values for NPV_{chain} of both instances are quite similar, the big difference in the *NPV* value is a consequence of the result for the

NPV_{car}, which is much bigger in instance B, supported by a big EVs market share of about 12% at *t*=5 against the 3.26% of instance A. The downside of these configurations is their environmental performance. The total GHG emissions both for instance A and B are, respectively, 10% and 9% superior to the ones related to petrol.

Regarding the environmental optimization, the addition of the new biomasses did not have any noticeable consequences on the performance. Even though one of these new biomasses is considered to be a residue from forestry activities, as it happened in the original model the preferred biomass for power production is still stover, which is also a residue. This happened because, since there is no fixed demand for power and ethanol, the production of ethanol was promoted by the solver in DGP (*k*=1) and LCEP (*k*=2) technologies, which bury fewer environmental impacts. Electricity production is only done in LCEP as a by-product.

Although both instances present very good environmental performances with GHG emissions of 38% and 16%, respectively for A and B, from the ones associated to petrol, these configurations are unfeasible, given the fact that their *NPV* is negative. The operation of these systems would only be possible under a strong support policy, with governmental incentives of 3.35 €/GJ for instance A and 4.84 €/GJ for instance B, which adds up to a total of $1.17*10^9$ € and $1.70*10^9$ € over the 15 years, respectively.

The second objective of this thesis was to analyze the effect of using different methods to assess the environmental impacts on the SC structure. Each of these methods uses different impact categories and normalization rules for the values attributed to those categories to assess the total impacts.

Applying the methods, different SC configurations and economic performances were obtained for all of them. Although the SC design varies a lot from method to method not only in terms of the conversion technologies used, but also in terms of the biomass type used as feedstock, all the solutions presented a bigger ethanol production rate. The variation in the economic performance, which goes from $-2.31*10^9$ € to $-6.66*10^8$ € cannot be ignored. In this sense, before developing an energy SC project, the decision makers must select the adequate environmental impact assessment method to be used, according to the purpose and scope of the project.

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