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Assessment of Global Sustainability of Bioenergy Production in a Water-Food-Energy Perspective

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One of most demanding problems for decision makers and for process engineers is the design of a proper energy strategy to guarantee clean energy supply. This problem is complex and cannot be assessed considering only the standard efficiency criteria used in the past. The process of energy production needs to be analyzed in its completeness, *from seed to consumption*. This paper deals with the issue of bioenergy production following a nexus perspective, considering the link among water, food and energy. In particular, an objective function depending on the most important resources required in bioenergy production is defined so that it can be simply optimized. Considering the parameter interrelationship among water, food and land (the so-called water-food-energy nexus) the method gives the instruments to determine, in one single function, the optimal condition with respect to these resources.
Two cases of study are analysed, dissimilar regarding the geographical location, environmental resources availability for energy production and food security.
Results show how the proposed method is able to describe the present sustainability of bioenergy production in a certain site. Furthermore, it can help to investigate the existence of bottlenecks related to the current situation of the site and, at the same time, it can highlight future opportunities in producing sustainable bioenergy.

1. Introduction

In the current context of increasing energy demand, concern for climate change and rising interest for energy independence, a lot of research effort has been put in the development of technological solutions for the production of energy from renewable resources (Zhang 2013). In this sense, biomass energy is an exemplary case, because of the broad spectrum of possible feedstocks and processes available for its production. Energy production from biomasses is though not free from controversial issues (Finley et al. 2014). In particular, if compared to other energy resources, biomasses rise new problems coming from the competition for natural resources between food and energy. This issue is here addressed with the water-food-energy nexus perspective. The nexus describes the complex inter-relationship, which takes place between energy and food production, in particular taking into account the water use in biofuel crops cultivation.
Food vs Bioenergy competition can arise because crops otherwise cultivated for human or animal feed (e.g. maize, soybean, palm oil etc.) are used as a feedstock for fermentation into biochemical. This cause a net loss of food, or/and can give input to the competition in the use of land and land-based resources such as water used for producing food and energy crops. Water and land are the most commonly considered resources core of the food vs energy competition, while the conflict food-energy related to edible crop in energy production is solvable by using different feedstocks (2nd generation biofuels) the conflict for water and land is much more afflictive. The cultivation of special crops for biofuel (e.g. Jathropha) requires in any case large quantities of water and land. Even the use of waste as feedstock is not free of water footprint. The scope of this paper is to use an index for sustainability assessment of 1st generation biofuel, the Nexus Index (Moioli et al. 2016), to

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assess the effectiveness of different policies used to produce energy from biomasses. The Nexus Index addresses the complexity of water-food-energy nexus in a synthetic indicator, which summarize the inter-relation of parameters as efficiencies, giving the result as a normalized performance. The use of Nexus Index allows comparing the efficiency of the base case (1st generation biofuel production) with some additional policies operated to increase energy production and efficiency. These policies can contribute to change any element of the nexus, but the use of the complete indicator is fundamental to understand the effect on the whole system. For better understanding how important is to deal with the problem of bioenergy production by considering all the elements of the nexus two different case studies are analysed and the effects of the same strategies in the two different conditions are compared. On the base of the result of analysis, it is possible to draw some general tendencies and the rank of importance of the various parameters, defining the best technological solutions for energy production in a specific geographical context.

2. Materials and methods

As mentioned above, the starting point of the study was the application of Nexus Index to the current biofuel production. The formula of Nexus Index is expressible as:

$$N.I. = \eta_{water}\eta_{food}\eta_{land} \tag{1}$$

Water efficiency is the key factor of nexus index and requires a further step to be completely defined. For this reason it is divided in two parts: quantitative water efficiency, which defines the efficiency in water use as a function of the lowest footprint possible, and qualitative water efficiency, which further define the water footprint, assessing the typology of water resource used in energy production. Food efficiency is required to define the capability of a country to provide food to the population and the relationship between energy and food production. Land efficiency assess the efficiency in land use as a function of agricultural yield and land availability.

For 1st generation biofuel, nexus index is calculated using data from water footprint of bioenergy (Gerber-Leenes et al. 2009) and from Faostat for the part of food and land efficiency. In order to evaluate the potential of the 2nd generation biomasses, two case studies are chosen. The first case study is a developing country. The choice for this study is Sierra Leone. The country was selected because it has relatively high arable area and a large availability of water; these two factors make the country a perfect candidate for the use of bioenergy to reduce the lack of energy. In the case study of an industrialized area, the choice goes to Lombardy, because of the large agricultural production available in a highly industrialized area. For the calculation of Nexus index for 2nd generation biomasses, it is necessary to choose some appropriate model for energy recovery from a specific waste feed. In this way, it is possible to determine the best technological solution among the selected and to compare its performance to 1st generation biofuels. In order to gather this information, two models are used: a simple gasification in the absence of steam (Zheng et al. 2006) and a solar driven gasification (Ravaghi-Ardebili 2015). To simplify the calculations we only considered the use of rice and rice husk as a feedstock. Rice was chosen because it is largely available in both the considered case studies (tab 1).

Table 1: major agricultural products in (a) Sierra Leone, (b) Lombardy

Item	Production [Mton/y]	Item	Production [Mton/y]
Rice	1,255	Maize	2,813
Potatoes	225	Rice	1,807
Palm oil	210	Wheat	551
Groundnuts	93	Oil seeds	319
Sugar cane	77	Soya	123
SierraLeone		**Lombardy**	

The nexus index was recalculated updating all the three elements with the effects generated by the new process configuration (increased energy production, increased resources consumption).

3. Results

In this section, the results will be sorted by case study. The two cases are compared to assess the different starting conditions. Nexus index is calculated for the two cases for the crops most used in biofuel production. The results are shown in figure 1.

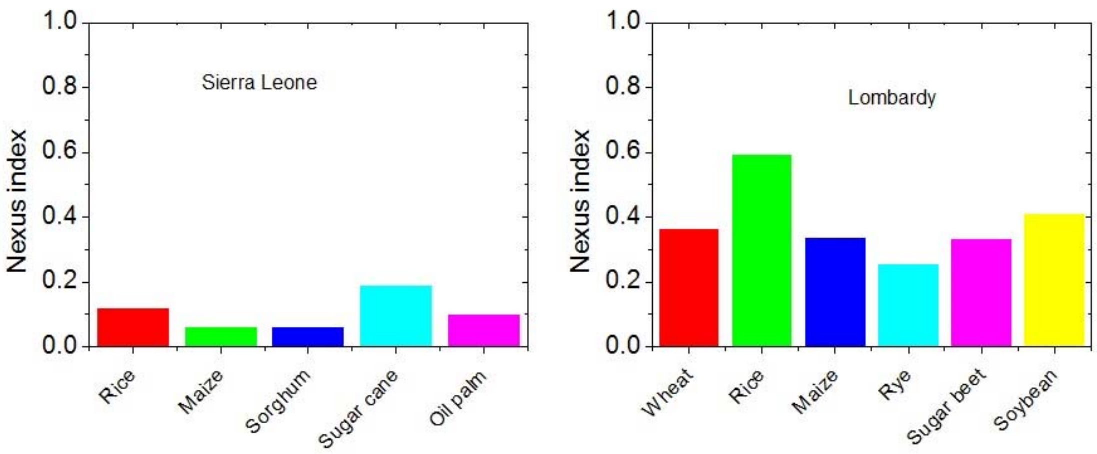

Figure 1. Nexus index for 1st generation biofuels for (a) Sierra Leone (b) Lombardy

These graphs confirm the great difference in efficiency between the two selected cases, due to several aspects. The main difference comes from the higher agricultural efficiency which can be reached with high industrialized cultivation techniques. This has a direct influence on both water and land consumption, because it allows recovering more energy using less water and dedicating less land to reach a specified production. Nevertheless, the main problem for Sierra Leone is given by food efficiency, which is blocked to 0.63. This model does not allow to consider efficient a country where part of the population suffer undernourishment, so the first focus of our study will be to assess the sensitivity of the results to this parameter.

3.1 Sierra Leone

We defined three different scenarios for Sierra Leone: increase of cultivated area to fulfil the food requirements and gasification (with air and steam) of the residuals of this production, increase of agricultural production and pyrolysis (only with air) of the residuals and only increase of energy production by use of current waste production. To simplify the calculation, we adopted some limiting assumptions:

- Use of rice as feedstock (already discussed in the previous section)
- Increase of the agricultural area by cultivation of rice (not considering the possibility of using a more suitable mix)
- Fulfil of the food calories requirement only with rice (this is a limiting hypothesis, because it simplify malnutrition to a lack of calories, without considering the requirements of specific micronutrients)

These assumptions allow us to limit the calculations to a single crop, with meaningful results without the need of mediation on several feedstock.

The results are displayed in figure 2, in form of percentage of increase or decrease from the base case.

For the case 1, the nexus index is almost doubled. This is due for a major part to the increase in food efficiency, since the problem of malnutrition is considered to be almost solved by the increased production of food. The quantitative part of water efficiency is increased of 30%; thanks to energy production with a higher efficiency than 1st generation case (the additional requirement of water per additional unit of energy is limited). A confirmation of the relative robustness of the country in terms of water availability comes from the qualitative water efficiency. Even though not negligible quantities of freshwater (blue water footprint) are required for the gasification of the agricultural waste, the qualitative water efficiency is not decreased. The resources of water of the country are large, so the use of water in a chemical process is not as critical as it could be in other contexts. The only element suffering because of the assumptions of this scenario is land efficiency. This value is decreased of 10%, because more arable land is considered to be exploited for rice production. The decrease in efficiency is however limited, a negligible value if compared to the highly beneficial effect on food efficiency. The case 2 is similar to case 1, since it applies the same cultivation strategy, just changing the technology used for biogas production to a scheme without additional water requirements. This second case has a lower increase of nexus index than the previous, because less energy is produced for unit of feedstock. The nexus index increase is 66%. In the specific case of Sierra Leone, it is not necessary in principle to avoid water consumption in biomass upgrading, thanks to the large water availability. This is well stated by qualitative water efficiency, which does not change in the two cases. From a first principle point of view, the controlling parameter for global sustainability is energy efficiency, since all the other parameter are already at the highest value possible. This means the solution 1 can be considered the best, even though it could not appear applicable for various technical problems (e.g. minimum size required). As a comparison, we also assessed the case of energy production from waste without increase of food production. In these conditions, even though the scores for water efficiency are the same, the nexus index has still low value, due to the large influence of food efficiency to global efficiency. This appears to be a quantification of the common sense that it is not efficient to produce energy from biomasses when large sectors of population suffer from undernourishment.

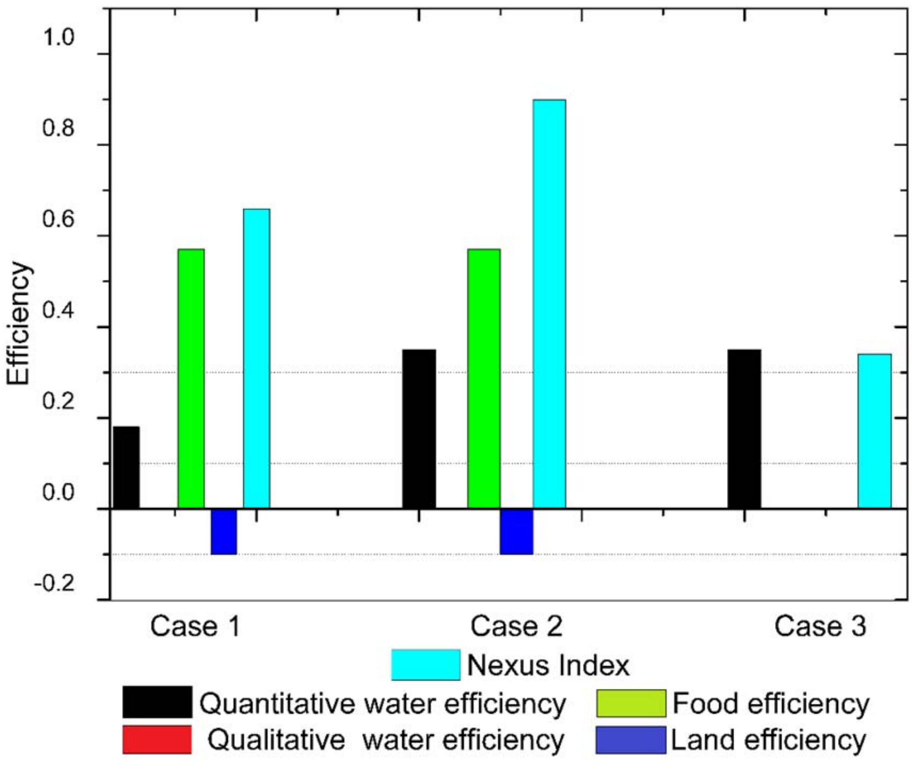

Figure 2. Change in the efficiencies composing Nexus Index for the 3 alternatives

To sum up the case of Sierra Leone, we can say that:

- The first important problem to solve is undernourishment, which, if not solved, does not allow increasing substantially the sustainability of energy production from biomasses.
- There is flexibility in the design of technological solutions, because water and land are not critical resources as of the current situation.
- The situation can also strongly change when considering other type of feedstock, since they may require higher quantities of land or water to be produced. In this sense, rice is a good option for the characteristics of cultivation in Sierra Leone.
- The most suitable solution to apply can be so designed taking into account the feasibility and limits due to external factors, such as grid connection or availability of the feedstock. According to this, it would be important to design the most suitable solution in terms of number and size of power plants.

3.2 Lombardy

The case of Lombardy is substantially different. In this region, there is high availability of water, but land availability is problematic, since most of the land suitable for agriculture has already been consumed and the high population density causes stress on the available free space. A similar approach to the previous case is developed in order to assess the potentiality of second generation biomass to increase energy sustainability.

In the first two case production of rice is increased to cover all the land currently available. The feedstock recovered in this way is then used for the contemporary production of 1st and 2nd generation bioenergy with gasification in the presence or absence of steam. In the third case, an identical quantity of energy is produced starting from material cultivated in the current situation. This allow to assess the sensitivity to the land factor.
The results of the calculations are reported in figure 3.

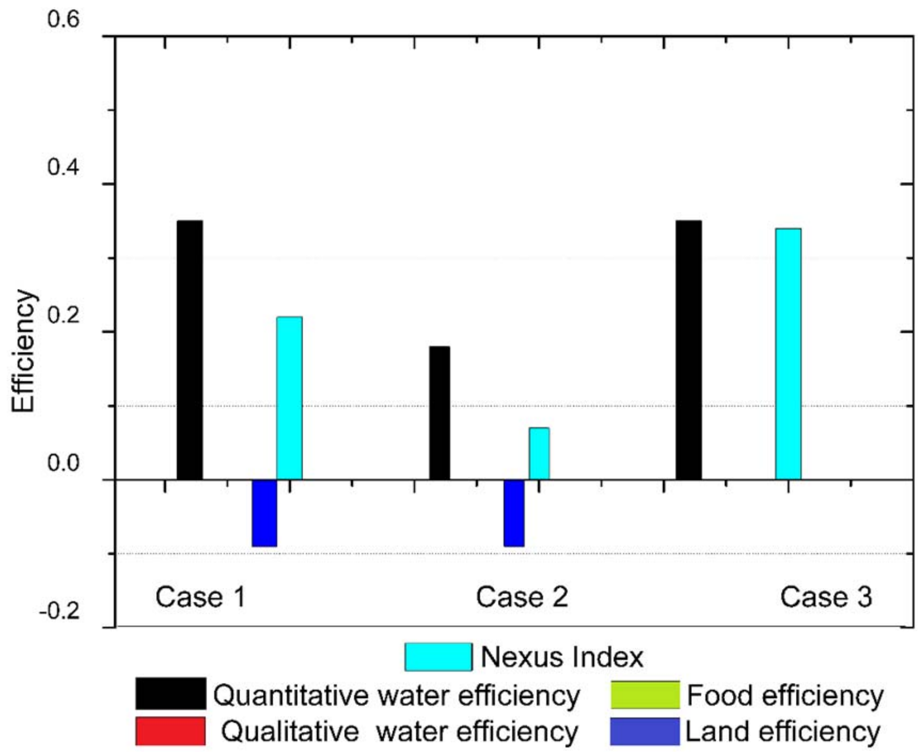

Figure 3. Change in the efficiencies composing Nexus Index for the 3 alternatives

Before looking at the results, it is important to observe how the production of 1st generation biofuel from rice is already efficient for Lombardy. Its water efficiency is among the highest in the world and the final value for nexus index is 0.6. This means that a further increase in the index means the attainment of very high values of global sustainability of the process.
In the first case analysed, the increase of quantitative water efficiency is 35%. It is important to observe that the absolute value of this efficiency is higher than 1; this happens because the quantity of energy recovered from one unit of feedstock is higher than the maximum value attainable only with 1st generation bioenergy production. Qualitative water efficiency is not changed going from the standard case to this case study, thanks to the large water availability in the area. A big decrease in land efficiency is observed (ca. 10%). This is the effect of the saturation of the available land and the penalisation is given because of the critical management of this resource.
The product of these two effects limits the advantage in global sustainability of the process, as stated by Nexus Index, which is increased of 22 %. Case 2 is also more affected by inefficiency in land management. Since quantitative water efficiency increases less than in case 1 (and qualitative water efficiency is not changed), the penalty for land saturation is stronger, limiting the final Nexus Index increase to 7%. This critical aspect found in the first two cases makes the third case study much more convenient. Without interfering to land management, the use of rice husk from already used land as a feedstock for gasification gives better results. The increase in nexus index coincides with the increase in water efficiency, which is 35%. These examples show how, according to the specific localisation of the production, different problems can arise, even if proposing similar process schemes. The optimal point reached in one place could not result in a similar performance in a different place. An additional important consideration comes from the deep analysis of land efficiency: in the case of Lombardy this limit is important also for 1st generation biofuels; it is not possible to increase the amount of agricultural feedstock for energy purposes without incurring in a decrease of the

sustainability of bioenergy production. The lesson learnt from these case studies draws a scenario where the policies to increase renewable energy production from biomasses should consider at first the possibility to increase agricultural yield and reduce water requirements; if these objectives are not reached, the only sustainable way of producing bioenergy is the effective coupling of food production and 2nd generation bioenergy production.

4. Conclusions

This study has shown how the optimisation of the problem concerning bioenergy production is complex and cannot be considered with standard optimisation parameters. For a complete understanding of the problem it is necessary to include in the formulation not only process efficiency, but also the effective consumption of all the resources required. This is a complex task, because it brings to the inclusion of non-standardized parameters, like geographical position and relationship with the area surrounding a production site. Through the use of 2 different case studies, the problem is assessed in different situations. We have seen how in a developing country, with problems of population undernourishment, the production of food is the bottleneck, which does not allow optimizing the process without considering it. In industrialized countries, where the problem of undernourishment is considered to be substantially absent, other problems may rise, like the risk of saturation of the available resources. This last point is very important while designing a process for 2nd generation biomass energy production, because hidden resources consumption can be present. For all these reasons, an integrated overview on these processes is necessary, like proposed in the Biorefill concept (Manenti et al. 2014). The biggest advances in global sustainability can be made only addressing a complex problem in a multidisciplinary approach, including in the model the contribution of all the fields touched by the designed process. For these reasons, we have pointed out that the nexus index can be considered as a robust optimisation instrument, which is able to assess different problems, complying with the requirements of flexibility, comprehension of the problems and simplicity of use in a conceptual design context.

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