ENVIRONMENTAL AND SOCIAL SUSTAINABILITY AND SUPPLY CHAIN EFFICIENCY IN THE PRODUCTION OF BIOMASS ENERGY

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The aim of the paper is to present a coordinated framework of the researches conducted by GESAAF - Department of the University of Florence, with a specific regard to the environmental and socio-economic sustainability of supply energy chains and local energy districts. The common feature of the researches is to provide a planning decision support able to considering the geographic variability of ecological, environmental and social characteristics of the territory. Modellisation of the analysed system was developed applying operational research based on multi-objective spatial analysis and optimization procedures. Conventional financial indicators and parameters to assess the best logistics of the chain were depicted in the evaluation. In addition, the researches introduced innovative performance indicators, such as the potential positive and/or negative impacts on ecosystem services, the trade-off between the production of residues for energy purposes and other wooded assortments and the analysis of acceptance of biomass plant by local stakeholders and the local community. Moreover, SensorWebEnergy technologies and computing platforms were developed not only to ensure the dissemination of technologies, results and technical and management experiences of supply chains, but also to ensure a constant monitoring of the production activities of the bioenergy chain. In other terms, Decision Support Systems, which are able to auto-calibrate in relation to the evolution of environmental, logistics and managerial parameters of the supply chains, were implemented.

Keywords: wood-energy chain, sustainability, operational research, decision support systems.
Parole chiave: filiera legno-energia, sostenibilità, ricerca operativa, sistemi di supporto alle decisioni.

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1. Introduction

Wood biomass was the most important source of energy for thousands of years, until the advent of fossil fuels. A new interest for this kind of renewable energy is emerging in the last decade, in particular due to financial and climatic dynamics (Demirbas *et al*., 2009).
The characteristics of the European area, particularly those of the Italian territory, suggest that the exploitation of wood-energy sources can attain a high level of importance for bioenergy production in these areas. However, the variability of national rural areas in terms of geomorphology, species composition, infrastructures and socio-economic issues implies that the sustainable development of the forestry energy chain has to consider environmental and socio-economic impacts in a comprehensive way. Thus, the use of flexible tools and Decision Support Systems (DSS) to plan bioenergy chain and to facilitate communication between researchers, policy makers and local stakeholders, is required. One of the main limits for the analysis and management of the chain highlighted in the current forest energy planning is attributable to the link between definition and practical application of "sustainability". Indeed, as stated in Kharrazi *et al*. (2014), the concept of sustainability often remains elusive and several attempts to construct a framework towards the quantification of sustainability have been made. In addition, even though several attempts for bioenergy chain optimization have been carried out (De Meyer *et al*., 2014), the implementation of a holistic analysis of impacts in local and global perspective and for current and future processes is a difficult task to define. Moreover, as affirmed by Wright *et al*. (2011), a disparity between the existing model-oriented bio-energy DSS functions and what practitioners desire, exists.
Lastly, it must be not forgotten that the agro-forestry territory is a mixed public/private good with a relevant production of social externalities (landscape, habitat for wildlife, etc.): this involves political and institutional issues aimed at safeguard the production of public utilities.
To overcome these barriers, the implementation of innovative DSS, able to analyse and plan the bio-energy sector with both scientific and practical advances, is needed.

2. Application of operational research and decision support system in wood-energy chain: a case study

Within those premises, the paper aims to describe the main researches carried out by the Department of Agricultural, Food and Forest Systems Management (GESAAF) of the University of Florence to define a comprehensive evaluation of sustainability of forest wood-energy chain and its planning and management optimisation.
To achieve these purposes, different methodologies based on operational researches were applied and DSS implemented to give a practical aid to policy makers and local stakeholders.
The following sections will focus on the application of these methods and techniques to briefly describe: i) woodchip supply quantification, ii) biomass plant acceptance evaluation, iii) scenario analysis, trade-off and optimisation of wood-energy chain and iv) technology transfer application.

2.1 Woodchip supply quantification

Different methods are available in literature for the analysis of biomass potential from forest residues.
As expressed by Seuring and Müller (2008), those researches are still dominated by green/environmental issues. Social aspects and the integration of the three dimensions of sustainability are still rarely considered. In order to cope with these limits a holistic and open-source spatial-based model was implemented.
The model called "Biomasfor" (Sacchelli *et al*., 2013c) represents a development of the previous researches (Bernetti *et al*., 2004; Bernetti *et al*., 2009; Zambelli *et al*., 2012), being able to compute the availability of biomass related to main assortments and residues for energy production from forest stands. The structure of the model is based on a multistep approach that allows quantifying the ecological, technical, economic and sustainable bioenergy. "Ecological bioenergy" is based on prescribed yield of Forest Management Plans or on increment of different forest typologies. "Technical bioenergy" introduces the evaluation of forest where the extraction of biomass is possible; it takes into account the main characteristics of the forest terrain and morphology, the facilities as well as the typology of machinery applied in the production process.
The "economic bioenergy" is the part of the technical bioenergy that can be collected to supply heating plants or biomass terminals and that is associated to forest stands that have a positive stumpage value.
A quite innovative analysis of the model can be depicted in the so-called "sustainable bioenergy" that represents the amount of woodchip energy obtainable to prevent potential negative impact on Ecosystem Services (ES). This sub-model sets a limit in the extraction of biomass to minimize soil depletion and losses of water quality as well as to maintain biodiversity and fertility of forest stands. An additional computation of the sub-model is the quantification of positive impacts on ES by taking into account the avoided carbon dioxide emission, the fire risk prevention and the potential tourist valorisation of the forests related to biomass extraction.

2.2 The biomass plant acceptance

Once potential demand and supply of bioenergy is defined, as well as logistics and facilities, it is possible to consider the implementation of biomass plants (for an in-depth analysis of biomass demand quantification see e.g. Nibbi *et al*., 2012). As often demonstrated in national and international case studies, public opposition, despite potential technical-economic and normative feasibility, could often thwart this kind of structure. This effect is usually called NIMBY (Not In My BackYard) effect.
In literature, a few methodologies are highlighted, which analyse this component of population perception. Among them, the information of population about ex-ante and ex-post characteristics of the intervention by participative processes is the most applied. However, the informative approach is a complex task to achieve due to the need of taking into account several variables in a unique framework and for the time used for the knowledge transfer.
In this sense an additional research aimed at carrying out a technique able to analyse and minimize NIMBY effect in case of planning of biomass facilities was conducted (Sacchelli, 2014).
In the research, an evaluation of complex systems and a maximization of biomass plant acceptance were defined by the application of Fuzzy Cognitive Map (FCM) procedure and nonlinear modelling.
The aim of the study was reached by the application of Social Cognitive Optimisation (SCO) evolutionary algorithm in a theoretical case study that quantified the perception of bioenergy sector's experts on a potential implementation of a Combined Heat and Power (CHP) plant. Preliminary results stressed how optimization procedure permits to define the main variables, steps and characteristics of the bioenergy chain on which to inform the local stakeholders and population through participative processes to minimize NIMBY effect and facilitate communication procedure of the project.

2.3 Analysis of scenario, trade-off and optimisation of wood-energy chain

The development of the above-described models represents a preliminary step for the analysis of woodchip energy chain sustainability. The combination of demand and supply availability has been applied to carried out different typologies of analysis. Some case studies are reported as examples as follows:
- scenario analysis;
- trade-off analysis;
- optimisation of bioenergy chain.

The scenario analysis mainly regards the application of sensitivity analysis of different input variables to define variation of supply and demand of bioenergy. Differences in biomass availability have been computed according to modulation of ecological, technical and economic parameters in several case studies (see e.g. Sacchelli *et al*., 2013c).

In the research, the scenario assessment framework defines not only the amount of biomass but also the supply/demand ratio and the economic value added for the entire forest chain giving alternatives to decision makers and a more holistic kind of output.
The integration of various sustainability parameters in a unique evaluation may lead to a conflict among socio-economic, environmental, technical and legal aspects. Therefore, in order to decrease these potential divergences and to set decision makers preferences, a trade-off analysis among different scenario is needed. An example of trade-off evaluation was applied by a multicriteria approach able to set the optimal level of biomass extraction at compartment level (Sacchelli *et al.*, 2013a). In this study, through the "distance from ideal point" technique, the modeller may define the best availability of woodchips assigning different weights to maintain diverse forest functions (i.e. the production of timber, the biodiversity and fertility maintenance, the fire risk prevention, etc.). Bioenergy production may also cause potential conflicts among production processes of different assortments. As an example of this, a case study regarded potential alternatives for coppices management in Tuscany (central Italy) was analysed, where the combined production of traditional assortments (firewood) and by-products (woodchips) as well as the exclusive production of woodchips were possible (Sacchelli *et al*., 2013b). By a sensitivity analysis based on wood products' prices, the Break Even Prices were calculated.
The Break Even Prices that switched the economic convenience from a particular production process to another one were defined for different forest typologies and geographic localisation. In addition, supply elasticity for firewood and bioenergy was computed. Optimisation of bioenergy systems took into account a partial equilibrium model able to quantify the socio-economic and environmental effects of policy, technology and best biomass allocation scenarios on the forest residue chain (Sacchelli *et al*., 2014). This GIS (Geographic Information System) based model can consider the financial trends and impacts on three forest compartments: sawmills, forest enterprises and energy plants. In addition to the above-mentioned parameters, the model computes avoided emissions for bio-heat and bioelectricity production and introduces an impact indicator for the road transport of biomass. Best logistics of bioenergy chain and best allocation of biomass from supply to demand were reached by solving different objective functions in a multi-objective linear programming model.
Lastly, the agro-energy districts planning appears as the crucial step for a correct assessment and management of bioenergy chain also from a normative point of view. In this context, within the project "The planning of the supply chain of agro-energy districts" (PRIN 2007)", a methodology for the identification of homogeneous areas for agro-energy demand and supply balance as well as for socio-economic characteristics was set up (Bernetti *et al*., 2011). In the project, the different parameters representing municipality characteristics were aggregated by a SKATER (Spatial 'K'luster Analysis by Tree Edge Removal) approach, a method referred to a spatial constrained clustering. The determination of the bioenergy districts facilitated the identification of areas where rural policy and intervention might be applied.

2.4 Technology transfer

As mentioned in the introduction section, a disparity between the modellisation of bioenergy chain and the real needs of practitioners and policymakers is often shown in literature. Therefore, in the previously cited researches, a particular emphasis was given to the implementation of DSS able to help decision makers in their task. Innovation technologies and technology transfer were then considered as crucial objectives to attain in the studies. To achieve these goals, the models were applied in different real case studies to develop Energy Plans at municipality level for the demand/supply quantification. Additional application regarded scenario analysis and optimisation of bioenergy chain for different localisation of both public and private forest owners (see e.g. Fagarazzi *et al*., 2014a). It is worth noting that the supply evaluation model was preliminary implemented through the collaboration with different research partners and a with graphical interface able to facilitate communication among researchers and stake-holders. This interface is available as plug in for the open-source software QuantumGIS and GRASS GIS with the evaluation of additional renewable resources availability (wind, photovoltaic and hydroelectric energy) (Svadlenak-Gomez *et al*., 2013; Garegnani *et al*., 2015).

2.5 The energy-chain monitoring and the Sensor Web Energy technology

The recent achievements of open-source technologies, based on open platform, have offered a good opportunity for low-cost monitoring of bio-energy chains. The biomass-energy chain is currently an economic sector with low value added, in which the collection of data and information may be implemented only at low cost.
On the other hand, the constant monitoring of chains (flux of products, efficient use of fuels, etc.), is a major support for the validation of the DSS models previously described. Real-time monitoring of energy chains actually provides a way to test the effects of the DSSs and their subsequent self-calibration. Monitoring is thus a major tool of ensuring the economic and environmental sustainability of DSS and models. Within bio-energy chains some criticalities have been identified that might jeopardize the development of the sector:

- need to make energy production processes transparent to meet citizens' requirements in terms of environmental safety;
- need to ensure the highest use efficiency of wood biomasses, e.g. the maximum energy conversion efficiency;
- need to ensure the local origin of biomasses, so as to minimise the environmental impact due to transportation and maximise their efficiency in terms of economic growth of the area in which the plant is installed, and maintenance as well as management of the local area involved;

- need to facilitate the job of energy plant managers (district heating, cogenerators, etc.) To meet these needs as well as improve the DSS, recent research studies have been targeted towards the implementation of low-cost Sensor Web Energy systems, integrated with web platforms, where data are accessible on a real-time basis. SWE defines the term Sensor Web Energy as "Web accessible sensor networks and archived sensor data that can be discovered and accessed using standard protocols and application programming interfaces" (Botts *et al.*, 2008).

In particular, the sensors are defined from an engineering point of view as devices that convert a physical, chemical, or biological parameter (like temperature, wind speed, solar radiation, moisture, etc.) into an electrical signal (Bermudez *et al*., 2009).

In our case, data are sent by a GPRS data transmission module to a web platform named iBioNet (Intelligent Bioenergy Network), where data are processed, outputs are modeled and produced for data interpretation. Users may access the platform to check the functioning, efficiency and origin of biomasses, etc. The peculiarity of the SWE network is its "open architecture" that fits any type of plant: thermal, cogenerative, systems with boilers in series or parallel connection, rake-loading and leaf springs or load boxes systems; in short it fits the heterogeneous range of plants existing in different European Countries (Fagarazzi *et al.*, 2014a).

In the case of biomass-energy chains, the remote measurements required concern:

- definition of the origin of the fuels arriving at different plants, of the supplier and of business features;
- assessment of the amount of biomass used in different plants;
- assessment of the amount of energy produced by different plants;
- estimate of plant electrical energy consumption;
- estimate of plant energy efficiency;
- climate data acquisition (to check the correct thermal management);
- security data acquisition (like fire, water in the main compartment, voltage fluctuations, etc.).

On the iBioNet platform the SWE data are however integrated by laboratory data on the chemical quality of fuels and emissions, fine dust (PM 2.5, PM 10, total PM; Ozone, CO and CO_2; NO_2 and solar radiation, etc.) In this way the transparency of the production process is maximised (Fagarazzi *et al.*, 2014b).

3. Discussion and conclusion

The described methodologies and works aim to match and integrate research efforts and technology transfer opportunities, to optimize efficiency and sustainability of the bioenergy sector. The applied approaches will allow the use of operational researches and the implementation of Decision Support Systems for highly differentiated input datasets and a flexible updating. Dynamic spatial-temporal analysis will facilitate computation for different study areas, planning level, typology of bio-energy chain management and temporal horizons.

Future research would apply developed DSS for agricultural bioenergy chain evaluation and for different kind of biofuels. Socio-environmental analysis of biomass production could be conducted by the application of additional approaches such as bio-physical, Life Cycle Assessment (LCA) and Ecological Carbon Footprint (ECF).

The availability of biomass in rural sector will be calculated also for agricultural resources, through farm accounting and computation of indexes related to extraction of pruning residues from permanent crops (vineyard, olive growth, fruit trees, etc.) as well as material from dedicated crops (short rotation forestry). Eventually, affirmed and original quantitative technique could be merged to monetized impacts on ecosystem services by the application of neoclassical economics, market theory and political sciences.

RIASSUNTO

Sostenibilità ambientale e sociale ed efficienza di filiera nella produzione di energia da biomasse

Lo scopo del presente lavoro è quello di presentare un quadro coordinato delle ricerche condotte dal Dipartimento GESAAF dell'Università degli Studi di Firenze, relativamente alla sostenibilità ambientale e sociale e all'efficienza economica delle filiere e dei distretti energetici locali. Caratteristica comune delle ricerche presentate è quella di fornire un supporto decisionale alla pianificazione tenendo conto della variabilità geografica delle caratteristiche ecologiche, ambientali e sociali del territorio tramite approcci di ricerca operativa basati su analisi spaziale multi-obbiettivo e procedure di ottimizzazione. Oltre a indicatori di efficienza classici tra i quali indici economico-finanziari e parametri di analisi della miglior logistica, i diversi studi condotti hanno introdotto indicatori di valutazione innovativi, come ad esempio i possibili impatti - positivi e negativi legati alla produzione di biomassa - sui servizi ecosistemici, il trade-off produttivo tra residui a scopo energetico e ulteriori assortimenti legnosi forestali e l'analisi dell'accettazione degli impianti a biomassa da parte degli stakeholders e delle comunità locali. Sono state inoltre sviluppate tecnologie SensorWebEnergy e piattaforme informatiche atte a garantire non solo la divulgazione delle tecnologie, dei risultati e delle esperienze tecnico-gestionali delle filiere, ma anche capaci di fornire un costante monitoraggio delle attività produttive della filiera bioenergetica.

In altri termini sono stati implementati Sistemi di Supporto alle Decisioni (SSD) in grado di autocalibrarsi in relazione all'evoluzione dei parametri ambientali, logistici e gestionali delle filiere.

BIBLIOGRAPHY

Bermudez L., Delory E., O'Reilly T., del Rio Fernandez J., 2009 – *Ocean Observing Systems Demystified*. In: Proceedings of OCEANS 2009, *Marine Technology for Our Future: Global and Local Challenges*, Biloxi, MS, USA, October 2009; IEEE: New York, NY, USA, 2009; pp. 1–7.

Bernetti I., Fagarazzi C., Fratini R., 2004 – *A methodology to analyse the potential development of biomass-energy sector: an application in Tuscany*. Forest Policy and Economics, 6: 415-432. http://dx.doi.org/10.1016/j.forpol.2004.03.018

Bernetti I., Fagarazzi C., Sacchelli S., Ciampi C., 2009 – *I comparti forestale e di prima trasformazione del legno.* In: Mazzei T., Nocentini G. (a cura di) - Stima della potenzialità produttiva delle agrienergie in Toscana. ARSIA, pp. 43-70.

Bernetti I., Ciampi C., Sacchelli S., Marinelli A., 2011 – *La pianificazione di distretti agro-energetici. Un modello di analisi per la regione Toscana.* L'Italia Forestale e Montana, 66 (4): 305-320. http://dx.doi.org/10.4129/ifm.2011.4.05

Botts M., Percivall G., Reed C., Davidson J., 2008 – *OGC Sensor Web Enablement: Overview and High Level Architecture*. In: Proceedings of *GeoSensor Networks*, 2nd International Conference, GSN 2006, Boston, MA, USA, October 2006; Nittel S., Labrinidis A., Stefanidis A., Eds.; Lecture Notes In Computer Science; Springer: Berlin, Germany, 2008; Volume 4540, pp. 175-190.

De Meyer A., Cattrysse D., Rasinmäki J., Van Orshoven J., 2014 – *Methods to optimise the design and management of biomass-for-bioenergy supply chains: a review*. Renewable and Sustainable Energy Reviews, 31: 657-670. http://dx.doi.org/10.1016/j.rser.2013.12.036

Demirbas M.F., Balat M., Balat H., 2009 – *Potential contribution of biomass to the sustainable energy development*. Energy Conversion and Management, 50: 1746-1760. http://dx.doi.org/10.1016/j.enconman.2009.03.013

Fagarazzi C., Tirinnanzi A., Cozzi M., Di Napoli F., Romano S., 2014a – *The forest energy chain in Tuscany: economic feasibility and environmental effects of two types of biomass district heating plant.* Energies, 7 (9): 5899-5921. http://dx.doi.org/10.3390/en7095899

Fagarazzi C., Tirinnanzi A., Ciniero G., Zaldei A., Matese A., Beghi A., 2014b – *iBioNet: Osservatorio sulle filiere biomassa-energia*. Sherwood Foreste e alberi oggi, 205: 15-18, Compagnia delle Foreste.

Garegnani G., Geri F., Zambelli P., Grilli G., Sacchelli S., Paletto A., Curetti G., Ciolli M., Vettorato D., 2015 – *A new open source DSS for assessment and planning of renewable energy: r.green.* Geomatics Work book, FOSS4G Europe, Como, 12:39-49

Kharrazi A., Kraines S., Hoang L., Yarime M., 2014 – *Advancing quantification methods of sustainability: a critical examination emergy, exergy, ecological footprint, and ecological information-based approaches*. Ecological Indicators, 37: 81-89. http://dx.doi.org/10.1016/j.ecolind.2013.10.003

Nibbi L., Tirinnanzi A., Sacchelli S., Ciampi C., Fagarazzi C., 2012 – *Planning Future Biomass to Energy Facilities on a GIS Offer/Demand Basis: A Study for Tuscany, Italy*. Proceedings of 20th European Biomass Conference and Exhibition, 14-18, Milan.

Sacchelli S., De Meo I., Paletto A., 2013a – *Bioenergy production and forest multifunctionality: a trade-off analysis using multiscale GIS model in a case study in Italy*. Applied Energy, 104: 10-20. http://dx.doi.org/10.1016/j.apenergy.2012.11.038

Sacchelli S., Fagarazzi C., Bernetti I., 2013b – *Economic evaluation of forest biomass production in central Italy: a scenario assessment based on spatial analysis tool*. Biomass and Bioenergy 53, 1-10. http://dx.doi.org/10.1016/j.biombioe.2012.11.026

Sacchelli S., Zambelli P., Zatelli P., Ciolli M., 2013c – *Biomasfor – An open-source holistic model for the assessment of sustainable forest bioenergy*. iForest - Biogeosciences and Forestry, 6: 285-293.

Sacchelli S., 2014 – *Social acceptance optimization of biomass plants: a Fuzzy Cognitive Map and Evolutionary Algorithm application*. Chemical Engineering Transactions, 37: 181-186.

Sacchelli S., Bernetti I., De Meo I., Fiori L., Paletto A., Zambelli P., Ciolli M., 2014 – *Matching socio-economic and environmental efficiency of wood-residues energy chain: a partial equilibrium model for a case study in Alpine area*. Journal of Cleaner Production, 66: 431-442. http://dx.doi.org/10.1016/j.jclepro.2013.11.059

Seuring S., Müller M., 2008 – *From a literature review to a conceptual framework for sustainable supply chain management.* Journal of Cleaner Production, 16 (15): 1699-1710. http://dx.doi.org/10.1016/j.jclepro.2008.04.020

Svadlenak-Gomez K., Badura M., Kraxner F., Fuss S., Vettorato D., Walzer C., 2013 – *Valuing Alpine ecosystems: The recharge.green project will help decision-makers to reconcile renewable energy production and biodiversity conservation in the Alps.* Eco.mont, 5: 59-62.

Wright D., Dey P., Brammer J., Hunt P., 2011 – *Bioenergy Decision Support Systems: worth the effort?* Proceedings of the World Renewable Energy Congress 2011, Linköping, Sweden, pp. 9-16. http://dx.doi.org/10.3384/ecp110579

Zambelli P., Lora C., Spinelli R., Tattoni C., Vitti A., Zatelli P., Ciolli M., 2012 – *A GIS decision support system for regional forest management to assess biomass availability for renewable energy production*. Environmental Modelling and Software, 38: 203-213. http://dx.doi.org/10.1016/j.envsoft.2012.05.01