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Matching socio-economic and environmental efficiency of wood-residues energy chain: a partial equilibrium model for a case study in Alpine area

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ABSTRACT

Combining the economics and the environmental and social aspects of bioenergy chain implementation is a difficult task, particularly for wood fuel production. Multiple aspects, such as financial analysis, technology development, natural resource exploitation and avoided environmental pollution, must be considered simultaneously. Thus, decision support models seem to be the proper tools for the overall definition of strategies in the wood energy sector.

The objective of this study has been to develop 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. The model, based on multi-objective linear programming and spatial analysis, considers the financial benefits/losses and the potential trends of three compartments: sawmills, forest enterprises and energy plants. In addition, the model computes avoided emissions for bioheat and bioelectricity production and introduces an impact indicator for the road transport of biomass. Model outputs are defined using a multi criteria approach. The main results stress the importance of both environmental parameters and the implementation of organic Rankine cycle technology for the optimization of the entire bioenergy chain. The model was tested in an Italian Alpine region (province of Trento).

1. Introduction

Woody biomass was the most important source of energy for thousands of years before the advent of fossil fuels. This type of renewable energy can now contribute to meeting the energy needs of modern society for both industrialized and developing countries. Recent forecasts project that worldwide wood-based electricity generation could increase to approximately 500% of 1995 levels in 2030 (Demirbas et al., 2009). This exponential interest in woody biomass must be coordinated with the accurate planning of this sector. In effect, sustainable exploitation of the agro-forestry energy chain must consider the social, economic and environmental impacts by analyzing technical-logistic, financial and natural issues.

At the local level, studies of bioenergy chains implementing the above-mentioned topics have been widely developed using different methodologies. Partial equilibrium models (PEMs) are one of the main techniques applied to analyze short or localized energy chains. A potential trade-off between food and non-food crops was developed by Ignaciuk et al. (2006), taking into account energy policies, land use consumption and bioenergy prices in Poland. The authors show, among other things, how incentives to bioelectricity production can increase both biomass and agricultural production. On the contrary, the carbon tax allows for a higher reduction of carbon dioxide emissions but also leads to the reduction of agricultural production. Johansson and Azar (2007) computed the same substitution effect for the US agricultural energy market using the non-linear optimization model LUCEA 2.0. In particular, a substantial increase in the prices of agricultural crops can be explained as an effect of carbon abatement policies. Focusing on the forest sector, Trømborg et al. (2008) defined the potential trends of the biomass market in Norway. In that paper, the main factor that could

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influence the competitiveness of bioenergy is the provision of economic subsidies. In addition, the introduction of small biomass plant technology shows higher efficiency than district heating systems, needing higher bioenergy prices or more incentives to be competitive. Susaeta et al. (2013) applied a PEM to establish the impact of the energy residues of southern US (Florida) forest industries on traditional assortments. The authors suggest that inclusion of incentive policies in bioenergy sector might generate benefits for the sector and for forest landowners, but economic losses for sawmill and pulpmill activities. PEMs have been applied for the forest energy sector in combination with several methodologies. Kallio et al. (2011) employed a PEM in a spatial analysis to evaluate the Finnish woodchip market. A technical and economic analysis of biomass-based cogeneration for the same region was carried out by Palander (2011) by the application of dynamic multiple-objective linear programming. Leduc (2009) described the geographically explicit bioenergy conversion optimization model BeWhere, which was based on mixed integer linear programming (MILP), developed using the commercial software GAMS and solved using CPLEX.

Impact assessments of forest residues on different bioenergy chain compartments were implemented by Schwarzbauer and Stern (2010) through the *Forst- und Holzwirtshaft* (FOHOW) model for Austrian forests. The authors projected competition between the energy sector and production by other wood-based industries (paper and panel) by the loss of gross profits and raw material procurement for industries. Analogous estimation was carried out for the sawmill sector by Ackom et al. (2010) for pellet and ethanol production in Canada and by Trømborg and Solberg (2010) for pulpwood and paper production in the Norwegian forest sector.

Competition analysis outlines how the prices and trade mechanisms of wood fuel can depend on policy and the global market (not only for the energy sector but also for other forest issues, such as transport, the industrial market, etc.; see, e.g., Trømborg and Solberg, 2010). In other cases, a conclusion is that "...demand and supply will develop differently in different regions and result in regional markets with regional prices unless storage and transportation technology of wood-based fuels will develop" (Olsson et al., 2010).

In this framework, this paper aims to develop a partial equilibrium analysis for the wood residue energy chain in the province of Trento (Italian Alps). Trento province can be considered representative of the entire Alpine region because it is affected by the same dynamic of social and landscape changes that can be found elsewhere in the Alps (Tattoni et al., 2010, 2011). Until now, the materials for the production of thermal energy in district heating (DH) plants in the study area have mainly been obtained from sawmill logging residues (Sacchelli et al., 2011). In fact, the use of biomass from silvicultural intervention presents several technical and economic problems in relation to the types of forests and the morphology of the land. However, technological and logistic improvements related to policy incentives and increased bioenergy demand could lead to a variation in the local wood residue market. Thus, an in-depth analysis is needed to furnish suitable guidelines to local stakeholders and policy makers. From a methodological viewpoint, the innovation of this work is the implementation of a partial equilibrium model inclusive of multi-objective linear programming and spatial analysis approaches.

Section 2.1 of this paper introduces the main bioenergy supply/demand characteristics of the system under study; the methodological framework is defined in Sections 2.2–2.5. Section 3 presents the main results of this work. Discussion and the potential further implementation and transferability of the model are defined in Section 4.

2. Applied methodology

Starting from a geodatabase of the bioenergy supply and demand of the province of Trento in northeast Italy (Sacchelli et al., 2011), the model depicts the consequences caused by the variation of current bioenergy chain characteristics based on socio-economic and environmental indicators. The value of each indicator was computed for different scenarios, derived from the combination of two parameters (incentive schemes for the bioenergy chain and new technological implementations of energy plants) and objective functions (related to optimal biomass allocation).

The results were aggregated into a Multi Criteria Analysis (compromise programming evaluation) to establish the best scenario. The general model framework is shown in Fig. 1. Symbology of equations is explained in Nomenclature section.

2.1. Study area and database

2.1.1. Supply analysis: sawmill residues

Approximately 84% of the woody biomass used for the production of thermal energy and electricity in heating plants is provided by sawmills. These data are based on an *ad hoc* survey conducted in 2010–2011 (Sacchelli et al., 2011). Questionnaires were distributed to a sample of sawmills operating in the province of Trento. This random sample was stratified based on forest districts (the province of Trento is subdivided into 10 forest districts defined as a cluster of municipality similar for socio-economic and territorial characteristics) and on the number of people employed (size of the sawmill). The total number of sawmills in the province of Trento is 105 units, and 59 sawmills were involved in this survey. Face-to-face interviews with the managers of the sawmills were conducted in 47% of the total sawmills, and 9% of the managers were reached by mail. Of the remaining 44%, the full sawmill activity and the number of employees were checked in 41% of the cases, and the data were not available for 3%.

The survey showed an annual quantity of processed roundwood of approximately 649,000 m^3, with an average ratio of processed timber to employee equal to 776 m^3/y. Most of the processed material was Norway spruce, silver fir and European larch. Of this wood, 65% came from the province of Trento and 19% from other regions of Italy, and 16% was imported from abroad. The declared average yield of the production process amounted to 70%, and the resulting residues were mainly woodchips (42%), sawdust (39%), slabs (13%) and bark (6%). The sampled sawmills provided an estimate of the total woodchips produced in the province of 202,157 MWh/y (equivalent energy content). The equivalent energy content was defined according to conversion units reported in Francescato and Antonini (2008).

Of the total residues produced in the provincial sawmills, 10% was self-consumed for the production of thermal energy (heating, drying of wood, etc.). The remaining portion was employed in various market sectors, such as biomass heating plants, gardening and nursery and wood processing industries (pellet or panel). Regarding the final use of the woodchips, Table 1 shows that 82% was allocated to the DH plants.

2.1.2. Demand analysis

At the province level, woodchip demand was estimated by considering existing large to medium DH plants (power above 400 kWt) and their future implementation. Small biomass plants for private users were previously investigated using random sampling (Sacchelli et al., 2011). Residues collected in small plants for energy production are a minimum percentage of the total biomass demand of the province (approximately 7.8% with 6% from sawmills and 1.8% from forests). Because of the small amount of biomass demand and installed power compared with DH and the absence of

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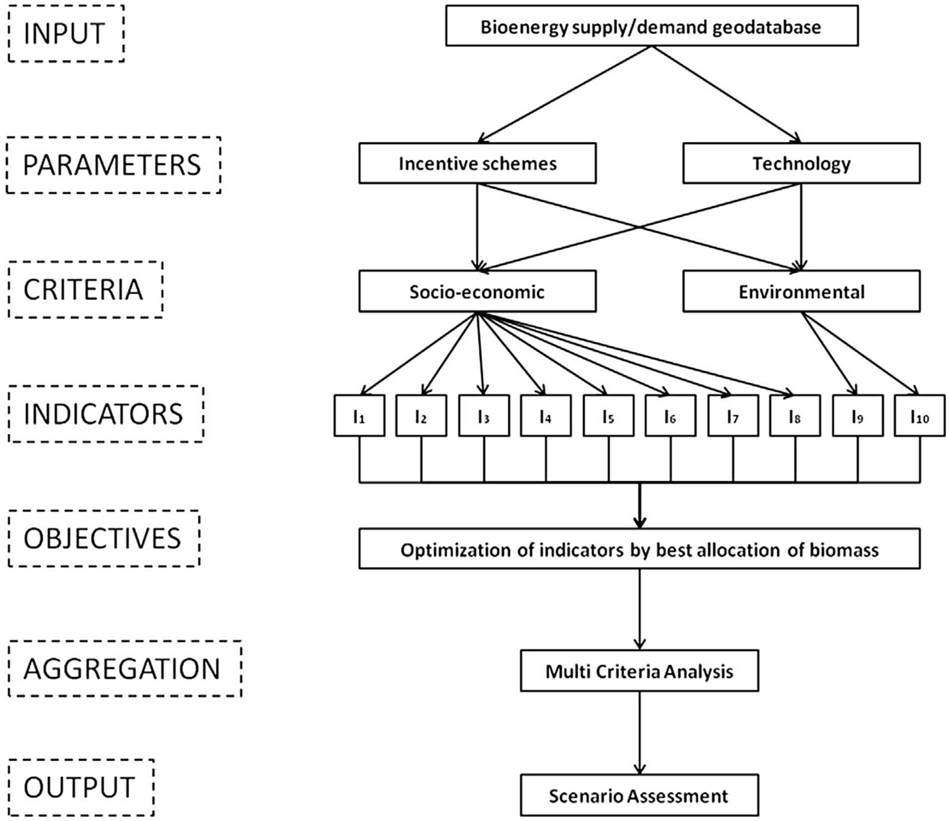

Fig. 1. General framework of the applied methodology.

a georeferenced database, these small plants were excluded from the analysis.

The total number of DH plants in the province of Trento was considered (15 units), and the information was collected through face-to-face interviews with the managers. The DH plants considered were built since 1999, mainly with the financial support of public authorities (Autonomous Province of Trento). The heating plants are mainly located in the northern region of the province, and all produce heat with woodchips. Six plants included generators powered by fossil fuels, while the use of other renewable energy sources (such as solar thermal or photovoltaic) was sporadic. The results of the survey indicated an installed capacity of 53.7 MWt, an annual requirement of woodchips equal to 107,357 MWh and a future requirement of 179,477 MWh/y (estimated by managers). Woodchips from local sawmills fulfilled more than four fifths of the total requirement, and the remaining portion was provided by logging companies or traders.

2.1.3. *Potential implementation of supply: forest residues*

The additional component of woodchip supply for the study area is represented by forest residues. Currently, the woodchip chain of forest enterprises in the province of Trento is partially implemented (Baldo et al., 2011). Woodchip market trends and increasing bioenergy demand suggest that the forest wood energy chain could increase its production (Zambelli et al., 2012). In this framework, the total potential future availability of bioenergy from forests was computed using the open-source spatial analysis model Biomasfor (Sacchelli et al., 2013a). Biomasfor quantifies the availability of forest wood energy biomass in light of ecological and economic sustainability and different typologies of mechanization. Forest biomass is identified as the tops and branches of final fellings and thinning material. To improve the bioenergy chain, the collection of woodchips at biomass terminals (BTs) was hypothesized. BTs could serve as collection points for wood fuel, facilitate bioenergy services and guarantee the provenance and quality standards of material (De Mol et al., 1997). In particular, the implementation of BTs should assist the optimization of biomass logistics to avoid barriers to energy efficiency. Effectively, both organizational and behavioral limits could exist at a local scale, and specific studies to observe and overcome these barriers must be carried out (Thollander and Ottosson, 2008).

Because of the absence of BTs in the province of Trento, their introduction was preliminarily localized in an optimal area according to a geographic multi criteria suitability model.

Optimal allocation combined forest resources and energy plant localization and selected an industrial area for construction (Van Dael et al., 2012). For each forest district, one BT was localized in the area BT_f, with the highest suitability score (Equation (1)).

$$\mathrm{BT_f} = \mathrm{MAX}\left(\sum_{i=1}^{\tau}\frac{(1-o_{i,f,a})+(1-d_{i,f,a})}{2}\right) \quad \forall i \in a \tag{1}$$
$$s.t.$$
$$a \geq 8000\ \ \mathrm{m}^2$$

Table 1
Final destinations of the woodchips produced by sawmills in the province of Trento.

Sector of consumption/sale	MWh/y	%
Province DH plants	90,970	45
Inter-province DH plants	74,798	37
Small biomass plants	12,128	6
Plants for pellet or panel production	4043	2
Self-consumption in sawmills	20,216	10
Total	202,157	100

Table 2
Quantification of forest residue energy per forest district.

Forest district	Energy availability (MWh/y)
Cavalese	$50122 \cdot 1.007^{pf_p}$
Fiera di Primiero	$25259 \cdot 1.009^{pf_p}$
Borgo Valsugana	$23265 \cdot 1.007^{pf_p}$
Pergine	$30522 \cdot 1.006^{pf_p}$
Trento	$12233 \cdot 1.001^{pf_p}$
Cles	$23863 \cdot 1.009^{pf_p}$
Malè	$35043 \cdot 1.009^{pf_p}$
Tione	$19188 \cdot 1.015^{pf_p}$
Riva del Garda	$4206 \cdot 1.022^{pf_p}$
Rovereto	$1884 \cdot 1.014^{pf_p}$

where τ is the number of pixels included in the *a-th* industrial area, $o_{i,f,a}$ is the normalized distance between the *i-th* pixel (included in the *a-th* area and the *f-th* forest district) and the forest supply, and $d_{i,f,a}$ is the normalized distance between the *i-th* pixel (included in the *a-th* area and the *f-th* forest district) and the energy plant. The limit of BT (8000 m^2), derived from Francescato et al. (2010), represents the minimum surface of BT required to permit the implementation of essential infrastructure and the maneuvering of trucks.

The amount of energy produced from forest residues, depending on the woodchip price, was quantified using the Biomasfor model (Table 2). This biomass represents the portion of the wood energy that can be efficiently collected at the BT from an economic viewpoint.

2.2. Model setting: parameters for scenario assessment

2.2.1. Incentive schemes

International, national and local policies promote the use of wood energy to improve the environmental and socio-economic benefits from global to local scales. Several examples are depicted in Directive 2009/28 EC on the promotion of the use of energy from renewable sources or in specific measures of the Communitarian Agricultural Policy (CAP) adopted at national and regional levels. Several funds have been established for bioenergy promotion, and new incentive schemes will be defined to extend the use of bioenergy. According to local policy (Provincial Energy Agency, 2012), the implementation of new energy plants will be encouraged. In addition, current forecasts suggest how potential incentives in the provincial wood energy chain could be provided to forest enterprises to increase woodchip production. In this context, the first criterion for scenario assessment is the potential incentive provision to the supply compartment. Therefore, three scenarios are considered, as follows: i) the absence of incentives to supply (Abs_{inc}), ii) incentives to the sawmill woodchip price (Inc_{saw}) and iii) incentives to the forest woodchip price (Inc_{for}). According to a proposal by local policy makers, a preliminary funding attempt was fixed at 2 €/MWh for both sawmill and forest woodchips (Provincial Energy Agency p.c.). National incentives due to energy production (green and white certificates, an all-inclusive tariff, etc.) have been preliminarily excluded to compute a cautionary estimation and to verify the self-maintenance of the future chain.

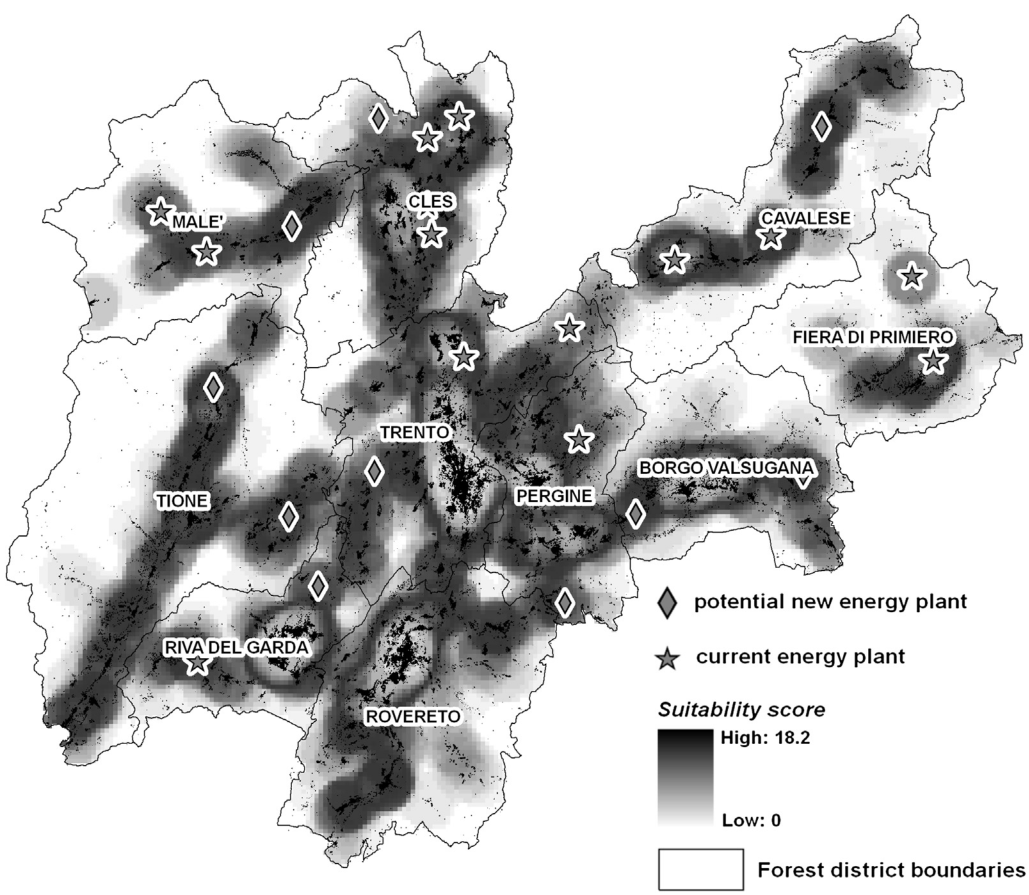

Fig. 2. Suitability of installation of new energy plants and localization of current and potential energy plants per forest district.

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2.2.2. Implementation of new technologies

Considering that the energy exploitation of forest residues should be based on short energy chains, the analysis has been performed considering the installation of small to medium-size plants. Moreover, in view of environmental sustainability, it was decided to maximize the overall energy efficiency; i.e., the heat produced by the plants had to be utilized as thermal power (for DH or process heat for industries) and not discharged into the environment as waste heat.

Three different typologies of plant configuration have been considered, all based on combustion: combined heat and power generation through a standard Rankine cycle (simply referred to as CHP below) or an organic Rankine cycle (ORC) and heat generation for district heating (DH). These configurations are more appropriate for small-scale woody biomass plants rather than more complex systems, such as steam or air gasification plants with internal combustion engines or gas turbines (Fiori and Florio, 2010).

The net power produced by both CHP and ORC plants has been fixed to the reasonable value of 1.5 MW_e, while the thermal power of DH has been set equal to 5 MW_t. In this regard, it is worth noting that ORC plants are currently considered for installation for power requirements between 0.5 and 2 MW_e, while CHP plants with counter-pressure steam turbines range between 1 and 50 MW_e. Thus, utilizing ORC plants of 1.5 MW_e completely fits with actual industrial installations, while CHP plants of 1.5 MW_e can be evaluated for installation (and installed) but are very close to their lower power limit. The technological limits of DH plants are practically nonexistent; the plants themselves are very simple. The scale-effect advice is to avoid plants that are too small. Furthermore, plants that are too large are normally not feasible because of the difficulties of installing large district heating piping and providing the plant with large amounts of locally produced biomass.

Our energy simulations account for the thermal and electrical efficiencies typical of these plants and their relevant size. The net electrical efficiency has been fixed at 19.5% and 15.5% for CHP and ORC, respectively. Thermal efficiency (i.e., thermal power available for utilization) has been fixed at 45%, 50% and 84% for CHP, ORC and DH, respectively. Thus, the overall efficiency (power plus thermal) for CHP and ORC is similar ($\approx$65%), with the former producing more power and the latter allowing for more thermal energy. Conversely, the two plant typologies present significant differences in terms of their flexibility, i.e., the capability of varying the load as a function of the (thermal) request. This aspect is particularly disadvantageous for CHP. In fact, considering that the plant's nominal power is very close its lower limit (as previously discussed), its load can only be decreased to a very limited extent, often failing to follow the thermal request. Because of this limitation, the installation of a CHP plant will also comprise a backup system capable of guaranteeing heat production and a system specifically devoted to satisfy thermal peaks. The establishment of these additional systems is less critical for ORC. ORC plants are more flexible than CHP plants and are thus more likely to be preferred for this type of small-scale application.

For each forest district, a distribution of new plants was hypothesized, as shown in Fig. 2. This localization depends on the supply/demand bioenergy ratio, computed according to a WISDOM analysis (Masera et al., 2006) and using a suitability model carried out following the approach of Nibbi et al. (2012). The total number of future new energy plants will depend on the above-mentioned technical limits. Three hypotheses have been considered with the installation of DH, CHP or ORC. More precisely, the number of plants has been defined using Equation (2) by considering the following variables: i) the potential future availability of biomass, ii) the amount of bioenergy needed at each plant, iii) the installation cost and iv) the amount of future funds applied by local policy makers to install new biomass plants (preliminarily hypothesized equal to 40 M€ one-time, according to the current provincial energy plan provision – Provincial Energy Agency, 2012).

$$
\begin{aligned}
&\max \sum_{e=1}^{y} \mathrm{NR}_e\\
&\text{s.t.}\\
&\sum_{e=1}^{y} C_e \le F\\
&\sum_{e=1}^{y} (W_e + E_e) \;=\; \sum_{e=1}^{y} (\alpha_e + \omega_e)\cdot h_e
\end{aligned}
\tag{2}
$$

where e is the e-th provincial energy plant (EP), y is the total number of EPs in the province, NR_e is the yearly net revenue for the e-th plant (see Section 2.3.1), and F is the funds provided for plant installation in the medium term (€).

Based on the above considerations, the analysis involves the potential implementation of 10 DH plants (DH scenario), 3 CHP plants (CHP scenario) or 8 ORC plants (ORC scenario).

2.3. Model setting: criteria and indicators

2.3.1. Socio-economic indicators

Financial evaluation of the provincial forest compartments was established by calculating the yearly net revenues linked to the energy residues market. In particular, the economic indicators are i) the yearly net revenues of the sawmills, ii) the yearly net revenues of forest enterprises and iii) the yearly net revenues of the energy plants.

Woodchips are produced by sawmills as a residue of the processing of timber and other main assortments. In a partial balance, the first cost related to residue production is the chipping cost (Yoshioka et al., 2002). According to the current market, woodchips could be used for energy production in provincial plants or sold on the interprovincial market (national bioenergy plants, panel production, etc.) for different prices.

Therefore, for each sawmill, net revenues NR_s were calculated as follows (Equation (3)):

$$
\begin{aligned}
&\mathrm{NR}_s \;=\; \left(\sum_{e=1}^{y} W_e\cdot \mathrm{ps}_p + \sum_{m=1}^{x} W_m\cdot \mathrm{ps}_m\right) - \left(\sum_{e=1}^{y} W_e + \sum_{m=1}^{x} W_m\right)\cdot \mathrm{cs} - \left(\sum_{e=1}^{y} W_e\cdot l_e\cdot tc_e + \sum_{m=1}^{x} W_m\cdot l_m\cdot tc_m\right)\\
&s.t.\\
&\begin{cases}
\left(\mathrm{ps}_p > \mathrm{ps}_m\right) \Rightarrow \sum_{e=1}^{y} W_e \;=\; \sum_{e=1}^{y} W_{e0} + \sum_{m=1}^{x} W_{m0}\\
\text{otherwise} \quad \sum_{e=1}^{y} W_e \;=\; \sum_{e=1}^{y} W_{e0}
\end{cases}
\end{aligned}
\tag{3}
$$

where m is the m-th interprovincial collection point and x is the total number of interprovincial collection points. The $ps_p > ps_m$ term defines two different potential conditions of the model based on the exogenous variables ps_p and ps_m. To maintain the linearity of the equations, these conditions have been set separately in the model.

The potential optimization of the forest residue chain suggests how the realization and management of BTs could be properly applied by forest enterprises (Wu et al., 2011). Following the approach used by Sacchelli et al. (2013a), the biomass collected from the forest and delivered to BTs is the chain that has a positive economic balance. The total profit for each forest enterprise NR_f must also consider the revenues from woodchip sales and the costs for the construction, operation and maintenance phases of BTs and the delivery of woodchips to the final plant (Equation (4)).

$$\mathrm{NR_f} = \left(\sum_{e=1}^{y} E_e \cdot \mathrm{pf}_p\right) - \left(\sum_{e=1}^{y} E_e \cdot j_e \cdot \mathrm{tc}_e\right) - q_f \tag{4}$$

The annualized net present value for each energy plant NR_e was expressed as a function of revenues from heating and/or electricity selling, construction cost and operating and maintenance costs (purchasing of woodchips, personnel cost, etc.) (Equation (5)).

$$\mathrm{NR}_e = \left(\sum_{n=0}^{\varphi} \frac{H_{e,n} \cdot \mathrm{pg} + T_{e,n} \cdot \mathrm{pt} - C_e - O_{e,n}}{(1+r)^n}\right) \cdot \frac{r \cdot (1+r)^n}{(1+r)^n - 1} \tag{5}$$

with

$$\begin{aligned} H_{e,n} &= \alpha_e \cdot \eta_e \cdot h_{e,n} \\ T_{e,n} &= \omega_e \cdot \lambda_e \cdot h_{e,n} \\ O_{e,n} &= M_{e,n} + P_{e,n} + \sum_{s=1}^{w} W_{e,s} \cdot \mathrm{ps}_p + \sum_{f=1}^{z} W_{e,f} \cdot \mathrm{ps}_p \end{aligned} \tag{6}$$

where n is the considered year in the cash flow and ϕ is the total cash flow period.

Net revenues of the entire bioenergy chain are expressed as follows (Equation (7)):

$$\mathrm{NR_{tot}} = \mathrm{NR}_s + \mathrm{NR}_f + \mathrm{NR}_e \tag{7}$$

The forest energy chain in the province of Trento is well established thanks to a long tradition of local resident rights[1] and the presence of DH since the end of the 1990s. The introduction of new bioenergy plants, forest process organization and specific funds and regulations could cause variations in the provincial energy market. These changes could also lead to increased or decreased efficiency of each enterprise (sawmill, forest enterprise, energy plant). Thus, social indicators highlight the risk of negative profit for these specific compartments. The implemented model develops a partial equilibrium analysis focused on the energy sector. This aspect suggests that the term "risk of negative profit" (RNP) does not refer to the entire production process but only to the residue market (e.g., an RNP for a sawmill is defined as equal to 1 if the economic balance of residue selling is negative and assumes a value of zero otherwise). RNP is considered not only an economic index but also a social evaluator. In fact, the strict relation between a production step and satellite activities could penalize the local market and employment rate.

Therefore, three additional socio-economic indicators were quantified: i) risk of negative profit for sawmills RNP_w, ii) risk of negative profit for forest enterprises RNP_z and iii) risk of negative profit for energy plants RNP_y (Equations (8)–(10), respectively).

$$\mathrm{RNP}_w = \frac{\sum_{s=1}^{w} \mathrm{RNP}_s}{w} \Big| \mathrm{RNP}_s = 0 \Rightarrow \mathrm{NR}_s > 0 \vee \mathrm{RNP}_s = 1 \Rightarrow \mathrm{NR}_s \le 0 \tag{8}$$

$$\mathrm{RNP}_z = \frac{\sum_{f=1}^{z} \mathrm{RNP}_f}{z} \Big| \mathrm{RNP}_f = 0 \Rightarrow \mathrm{NR}_f > 0 \vee \mathrm{RNP}_f = 1 \Rightarrow \mathrm{NR}_f \le 0 \tag{9}$$

$$\mathrm{RNP}_y = \frac{\sum_{e=1}^{y} \mathrm{RNP}_e}{y} \Big| \mathrm{RNP}_e = 0 \Rightarrow \mathrm{NR}_e > 0 \vee \mathrm{RNP}_e = 1 \Rightarrow \mathrm{NR}_e \le 0 \tag{10}$$

2.3.2. Environmental indicators

The environmental indicators are quantified by the avoided carbon dioxide emissions during bioenergy production, including both avoided emissions due to the combustion of renewable resources (woodchip) instead of fossil fuels and emissions during the transport phase. As for extraction of forest residues and collection to biomass terminal, also the optimal distance traveled from biomass terminals/sawmills to biomass plants considers the morphology of the land. In particular, in order to calculate the "transit weight", the model is based on a cost surface algorithm that combines linear distance (related to resolution of all crossed pixels in raster map) and slope of each crossed area (Bernetti et al., 2004).

Currently, woodchip transport in the local and national bioenergy chains is mainly truck-based (both truck and truck-and-trailer mechanization). Unless the greenhouse gas (GHG) emissions of this type of process are largely compensated by the avoided emissions of the combustion process in the energy plant (see, e.g., Valente et al., 2011), additional impacts of the transport phase could be considered. Literature analysis stresses how road traffic (truck-based transport in particular) could be criticized for its negative impacts on the perception of the inhabitants. Patil et al. (2011) show that one of the most important transport annoyances is noise. The distribution of annoyances highlights trucks as the main cause of noise (60%). In addition, health impairments and an increased risk of accidents are perceived by motorists in the case of heavy traffic caused by trucks (Dora and Phillips, 2000). Several papers focus on the impact of truck-based transport on the biomass chain. Economic efficiency (Ravula et al., 2008), traffic perception (ITABIA, 2008; Plate et al., 2010) and GHG emissions compared with other means of transport (Jäppinen et al., 2013) are several of the parameters considered. Because of the complexity in the definition and aggregation of the above variables, carbon dioxide emissions (strictly related to the distance traveled) were considered an independent indicator for the quantification of potential traffic annoyance in the present work. In conclusion, two environmental indicators were defined: i) total avoided CO_2 emissions related to bioenergy production and ii) potential traffic annoyance due to woodchip transport (Equations (11) and (12), respectively):

$$\begin{aligned} \mathrm{CD} = &\sum_{e=1}^{y} (\alpha_e \cdot h_{e,n} \cdot k_H + \omega_e \cdot h_{e,n} \cdot k_T) - \delta \\ &- \left(\sum_{e=1}^{y} W_e \cdot l_e + \sum_{m=1}^{x} W_m \cdot l_m - \sum_{e=1}^{y} E_e \cdot j_e\right) \cdot \gamma \end{aligned} \tag{11}$$

[1] Common property rights (*usi civici* in Italian) include the rights to gather firewood and cut timber (bote right), graze cattle and sheep, collect grass and leaf litter for cattle, gather fruits and mushrooms, hunt, fish, mine and design water-use regimes. In the communities of the province of Trento, the bote right is presently the most important common right, as firewood represents an important source for the heating of homes.

$$\mathrm{Ta} = \left(\sum_{e=1}^{y} W_e \cdot l_e + \sum_{m=1}^{x} W_m \cdot l_m - \sum_{e=1}^{y} E_e \cdot j_e \right) \cdot \gamma \quad (12)$$

2.4. Objective functions: optimization of indicators by the best allocation of biomass

The last factor of scenario assessment is the optimization of socio-economic and environmental indicators based on the optimal allocation of biomass from source to demand. A multi-objective linear programming approach was applied to maximize economic performance (Equations (13)–(16)), maximize avoided carbon dioxide emissions (Equation (17)) and minimize traffic annoyance (Equation (18)).

$$\max \sum_{s=1}^{w} \mathrm{NR}_s \quad (13)$$

$$\max \sum_{f=1}^{z} \mathrm{NR}_f \quad (14)$$

$$\max \sum_{e=1}^{y} \mathrm{NR}_e \quad (15)$$

$$\max \sum_{s=1}^{w} \sum_{f=1}^{z} \sum_{e=1}^{y} \left(\mathrm{NR}_s + \mathrm{NR}_f + \mathrm{NR}_e \right) = \max \sum_{s=1}^{w} \sum_{f=1}^{z} \sum_{e=1}^{y} \mathrm{NR}_{\mathrm{tot}} \quad (16)$$

$$\max \mathrm{CD} \quad (17)$$

$$\min \mathrm{Ta} \quad (18)$$

Equations (13)–(18) were subjected to non-negativity of the implied variables and to the following limits (the matching of bioenergy demand and supply; Equation (19)):

$$\sum_{e=1}^{y} (W_e + E_e) = \sum_{e=1}^{y} (\alpha_e + \omega_e) \cdot h_e \quad (19)$$

2.5. Aggregation of parameters and objective functions

To use biomass for energy production according to the concept of sustainability, it is necessary to define clear methodology for indicator aggregation that is able to identify the potential impact on socio-economic and environmental criteria. Multi Criteria Analysis (MCA) has been widely used in territorial planning because of its ability to aggregate variables characterized by different units of measurement and of otherwise contrasting types (e.g., qualitative and quantitative parameters) (Zeleny, 1982). An extensive literature review of MCA application in the bioenergy sector was carried out by Wang et al. (2009). The authors define a set of criteria and methodologies suitable to assess the sustainability of bioenergy systems. Buchholz et al. (2009a) analyzed different applications based on MCA methods; their work defines the possibilities of the integration of different MCA techniques, taking into account the uncertainty of the evaluation. Among several studies, different applications of MCA in biomass evaluation were also defined in Erdogmus et al. (2006) by the description of the Analytic Network Process (ANP) and in Buchholz et al. (2009b).

In the present work, scenario ranking was computed by the use of the Compromise Programming (CP) application (Malczewski, 1999) and computation of the distance from the Ideal Point (Carver, 1991). This methodology has been successfully applied to combine geographic information system (GIS) information and forest planning (Phua and Minowa, 2005). Recently, this methodology was integrated with both bioenergy and multifunctionality assessment in a GIS environment (Sacchelli et al., 2013b). The applied ideal point distance rule is:

$$D_\sigma = \left\{ \sum_{q=1}^{u} \left[\frac{\left(v'_{q,\sigma} - v_{q,\sigma} \right)}{\left(v'_{q,\sigma} - v^*_{q,\sigma} \right)} \right]^{\psi} \right\}^{1/\psi} \quad (20)$$

where D_σ is the distance from the ideal point in scenario σ, u is the number of q criteria, $v'_{q,\sigma}$ is the ideal value for the q-th criterion, $v_{ns,j}$ is the calculated value of the q-th criterion in scenario σ, $v^*_{q,\sigma}$ is the non-ideal value for the q-th criterion, and ψ is the metric used in the analysis (from "1", total compensatory approach to "∞", total non-compensatory approach). Following the literature review developed in Diaz-Balteiro and Romero (2008), a metric $\psi = 2$ was applied to provide a partial compensatory approach in the present work.

3. Results

Table 3 highlights the scenario ranking in terms of the best score achieved in CP aggregation. Scenarios combine the potential presence of incentive schemes, applied technology and the best allocation of biomass to optimize a specific objective function.

The best scenarios are those that combine ORC technology and biomass allocation able to minimize carbon dioxide emissions. Allocation of bioenergy that maximizes the annual net revenues of the energy plants is the worst parameter for global optimization. In this case, the net revenues of sawmills and forest enterprises are mainly negative. The total net revenues of the entire wood energy chain range from 2.58 to 9.07 M€/y. At the single compartment level, net revenues could vary from −0.92 to 2.55 M€/y for sawmills, from −2.44 to 3.08 M€/y for forest enterprises and from 3.45 to 6.10 M€/y for energy plants. The risk of negative profit should attain a critical value for sawmills and forest enterprises (ranging from 0% to 92% and from 10% to 100%, respectively), whereas this risk is generally low for energy plants. Avoided carbon dioxide emissions range between 0.087 and 0.11 Mt/y. The best performances are obtained by ORC plant implementation and, as expected, in the CO_2 minimization scenario. Emissions due to transportation range between 49 and 350 t/y.

Fig. 3 shows the influence of each criterion on the final results, expressed as the mean value of CP aggregation (distance from the ideal point). The best outcomes are outlined for the minimization of the CO_2 emissions of the entire chain and for the minimization of road transport. In addition, the maximization of total net revenue and the introduction of ORC technology appeared to obtain favorable results. The worst scores are associated with the allocation of biomass that maximizes the net revenues for energy plants and with the introduction of CHP technology. The latter result is caused mainly by the power limits of CHP. In fact, the energy efficiency of this plant does not permit the installation of power lower than 1 MW_e. Therefore, the supply/demand ratio constraint allows a lower number of new CHP plants to be installed compared with DHP or ORC technology.

Fig. 4 highlights the trend of indicators based on different criteria. The variation in economic and social indicators is mainly influenced by technology and allocation criteria (Fig. 4a and b). In the case of max_NR_s and max_NR_f scenario (allocation that fosters the maximization of net revenues), a conflict between sawmills and forest enterprises is clear. Another conflict is evident in RNP for the

Table 3
Scenario assessment.

Scenario[a]	NR_s (€)	NR_f (€)	NR_e (€)	NR_{tot} (€)	RNP_w	RNP_z	RNP_y	CD (t CO_2)	Ta (t CO_2)	$\psi = 2$
Inc$_{saw}$-ORC-max_CD	2,009,599	804758	5,502,938	8,317,296	0.27	0.40	0.00	105783	49	0.67
Inc$_{saw}$ -ORC-min_Ta	2,000,933	796,261	5502938	8,300,132	0.27	0.40	0.00	105783	49	0.68
Inc$_{for}$-ORC-min_Ta	1,174,890	1407285	5,579,830	8,162,005	0.20	0.30	0.00	105711	121	0.68
Inc$_{for}$-ORC-max_CD	1,174,890	1,407,285	5579830	8,162,005	0.20	0.30	0.00	105711	121	0.68
Abs$_{inc}$-ORC-min_Ta	1,188,194	985,703	5980158	8,154,054	0.19	0.30	0.00	105711	121	0.68
Abs$_{inc}$-ORC-max_CD	1,188,194	985,703	5,980,158	8,154,054	0.19	0.30	0.00	105711	121	0.68
Abs$_{inc}$-DH-max_NRtot	953,205	2,245,784	5,376,702	8,575,691	0.30	0.10	0.00	104089	163	0.76
Abs$_{inc}$-DH-min_Ta	1,243,595	975907	5307817	7,527,319	0.12	0.30	0.00	104124	127	0.76
Abs$_{inc}$-DH-max_CD	1,223,671	956,371	5,307,817	7,487,859	0.13	0.30	0.00	104124	127	0.77
Inc$_{for}$-DH-min_Ta	1,243,595	1,442,741	4861530	7,547,866	0.12	0.20	0.00	104125	127	0.78
Inc$_{for}$-DH-max_CD	1,223,671	1423205	4,861,530	7,508,406	0.13	0.20	0.00	104125	127	0.79
Abs$_{inc}$-ORC-max_NRtot	755,981	2,215,275	6,081,204	9,052,459	0.42	0.20	0.00	105674	158	0.80
Inc$_{for}$-ORC-max_NRtot	761,590	2,729,156	5583823	9,074,570	0.43	0.20	0.00	105675	157	0.82
Inc$_{for}$-DH-max_NRtot	974,588	2765997	4864209	8,604,794	0.30	0.10	0.00	104089	162	0.83
Inc$_{for}$-ORC-max_NRs	1,402,541	696,951	5,577,858	7,677,350	0.01	0.50	0.00	105657	175	0.87
Inc$_{saw}$-DH -max_NRtot	1,204,822	2271605	5149097	8,625,524	0.62	0.10	0.00	104149	103	0.89
Inc$_{saw}$-DH-max_CD	2,116,785	928,072	4,799,242	7,844,099	0.23	0.40	0.13	104198	53	0.90
Inc$_{saw}$-DH-min_Ta	2,116,785	928,072	4,799,242	7,844,099	0.23	0.40	0.13	104198	53	0.90
Inc$_{saw}$-ORC-max_NRtot	974,526	2,188,049	5,897,089	9059663	0.69	0.20	0.00	105736	97	0.92
Abs$_{inc}$-ORC-max_NRs	1,402,541	144,052	5,931,329	7,477,922	0.01	0.70	0.00	105658	174	1.04
Inc$_{for}$-DH-max_NRs	1,463,362	142765	4,859,798	6,465,925	0.00	0.50	0.00	104051	200	1.10
Abs$_{inc}$-DH-max_NRs	1,463,362	−285,005	5,262803	6441160	0.00	0.80	0.00	104070	182	1.24
Inc$_{for}$-ORC-max_NRf	−731,038	2,979,799	5584,920	7,833,681	0.58	0.10	0.00	105620	212	1.29
Abs$_{inc}$-ORC-max_NRf	−772,437	2,411,209	6104759	7743530	0.60	0.10	0.00	105618	214	1.30
Inc$_{saw}$-ORC-max_NRf	−608,482	2,411,209	5,979,912	7,782,638	0.89	0.10	0.00	105678	154	1.39
Abs$_{inc}$-DH-max_NRf	−917,311	2,502,526	5,384,718	6,969,932	0.58	0.10	0.00	104017	234	1.40
Inc$_{for}$-DH-max_NRf	−767,081	3,077,981	4,865,072	7,175,972	0.59	0.10	0.00	104024	227	1.41
Inc$_{saw}$-ORC-max_NRs	2,448,339	−1,772,841	5,268,900	5,944,398	0.03	1.00	0.00	105704	128	1.48
Inc$_{saw}$-DH-max_NRf	−869,732	2,502,526	5,202,494	6,835,287	0.81	0.10	0.00	104072	179	1.48
Inc$_{saw}$-DH-max_NRs	2,551,627	−218,100	4,546,969	6,880,497	0.01	0.80	0.29	104150	102	1.57
Abs$_{inc}$-CHP-min_Ta	1,010,388	923,845	4,172,301	6,106,534	0.26	0.30	0.18	86662	145	1.63
Abs$_{inc}$-CHP-max_CD	1,010,388	923,845	4,172,301	6,106,534	0.26	0.30	0.18	86662	145	1.63
Abs$_{inc}$-CHP-max_NRtot	687,287	1,892,531	4,237,423	6,817,241	0.40	0.10	0.18	86627	179	1.64
Inc$_{saw}$-CHP-max_NRtot	1,158,099	1,881,557	3,944,545	6,984,202	0.61	0.20	0.18	86697	109	1.68
Inc$_{saw}$-CHP-max_CD	1,654,086	763,547	3,749,670	6167303	0.44	0.30	0.18	86735	72	1.69
Inc$_{saw}$-CHP-min_Ta	1,652,890	758,296	3,749,670	6,160,857	0.44	0.30	0.18	86735	72	1.69
Inc$_{for}$-CHP-max_CD	1,005,438	1,387,542	3,719,377	6,112,357	0.26	0.30	0.18	86662	145	1.70
Inc$_{for}$-CHP-min_Ta	1,005,438	1,387,542	3,719,377	6,112,357	0.26	0.30	0.18	86662	145	1.70
Abs$_{inc}$-CHP-max_NRs	1,233,405	481,774	4,098,617	5,813,796	0.01	0.50	0.18	86632	174	1.71
Inc$_{for}$-CHP-max_NRtot	651,766	2,479,908	3,722,268	6,853,941	0.41	0.10	0.18	86626	180	1.73
Inc$_{for}$-CHP-max_NRs	1,233,405	875,365	3,716,543	5,825,313	0.01	0.50	0.18	86634	172	1.76
Abs$_{inc}$-CHP-max_NRf	−809,424	2,111,797	4,237,423	5,539,796	0.58	0.10	0.18	86586	220	1.96
Inc$_{saw}$-CHP-max_NRs	2,018,568	−826716	3,446,657	4,638,510	0.06	0.80	0.18	86680	126	2.00
Inc$_{for}$-CHP-max_NRf	−783,987	2,673,549	3,722,268	5611830	0.58	0.10	0.18	86587	220	2.02
Inc$_{for}$-ORC-max_NRe	−288,981	−1,718,582	5,584,920	3,577,357	0.61	0.80	0.00	105484	348	2.05
Inc$_{saw}$-CHP-max_NRf	−872,238	2,111,797	4,076,550	5,316,109	0.82	0.10	0.18	86638	168	2.06
Inc$_{saw}$-DH-max_NRe	69,589	−1,992,940	5,212,059	3,288,708	0.89	0.80	0.00	103983	268	2.08
Inc$_{for}$-DH-max_NRe	−324,636	−1,730,081	4,865,072	2,810,355	0.58	0.70	0.00	103902	349	2.11
Abs$_{inc}$-DH-max_NRe	−502,574	−2,007,133	5,389,594	2,879,886	0.58	0.80	0.00	103911	340	2.13
Abs$_{inc}$-ORC-max_NRe	−324,952	−2,439,319	6,104,759	3340488	0.60	1.00	0.00	105482	350	2.21
Inc$_{saw}$-ORC-max_NRe	−320,833	−2,250,721	5,979,912	3,408,357	0.92	1.00	0.00	105538	295	2.25
Abs$_{inc}$-CHP-max_NRe	−315,622	−1,105,400	4,242,300	2,821,278	0.59	0.70	0.18	86536	270	2.33
Inc$_{for}$-CHP-max_NRe	−302,414	−673,629	3,722,461	2,746,418	0.60	0.60	0.18	86528	278	2.36
Inc$_{saw}$-CHP-max_NRe	−400,672	−1,102,689	4,086,115	2,582,754	0.91	0.70	0.18	86586	220	2.45

[a] "Inc$_{saw}$", "Inc$_{for}$", "Abs$_{inc}$": incentive schemes as defined in Section 2.2.1. "ORC", "DH", "CHP": biomass plant technology as defined in Section 2.2.2. "max_CD", "min_Ta", "max_NR_tot", "max_NR$_s$", "max_NR$_f$", "max_NR$_e$": objective functions as defined in Section 2.4.

three sectors in the case of the different allocation of biomass. Environmental criteria and incentive schemes show reduced variability in indicator performance.

Fig. 4c introduces an additional indicator (Ta_prov), showing road transport emissions in the provincial market. It is interesting to note that road transport at the provincial level generally reaches a better value with respect to transport for the entire woodchip allocation. However, in the case of incentives to the sawmills, a portion of the biomass currently sold in the interprovincial market could be transferred to the local bioenergy chain. This aspect leads to an inversion of the above-mentioned statement.

An opportunity offered by the model is the spatial representation of the results. GIS-based outputs could facilitate the interpretation of information for each scenario. For example, Fig. 5 examines the best allocation of biomass from source to energy plant to minimize road transport and satisfy local demand. The same colors of source points and demand points mean that biomass is allocated from first to second ones (e.g. from sawmills/BTs to energy plants). Non colored symbols represent the lack of allocation of biomass in case of demand saturation. The scenario is based on the implementation of ORC plants with incentives on the forest woodchip price. The figure also suggests how the greater probability of RNP is depicted for sawmills and biomass terminals located in the southern region of the province. In fact, there are fewer energy plants in this area than in the northern region; consequently, the transport distances from supply to demand are higher.

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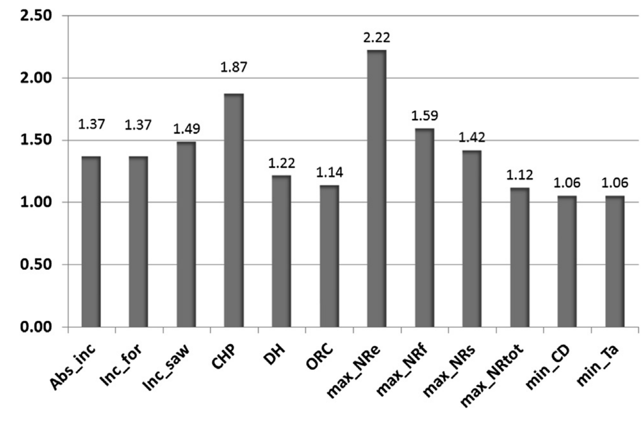

Fig. 3. Influence of the scenario parameters on total evaluation (distance from ideal point).

In addition, the low amount of forest residue both potentially decrease the economic performance of BT and make the implementation of new energy plants more difficult.

4. Discussion and conclusions

In the present work, the authors developed a partial equilibrium model able to quantify the socio-economic and environmental effects of policy, technology and optimization of biomass allocation on the forest residue chain. The results take into consideration the financial benefits/losses and potential trends of three compartments: sawmills, forest enterprises and energy plants in the province of Trento in the northeastern Italian Alps. Furthermore, environmental improvement was expressed as a function of avoided carbon dioxide emissions in the entire bioenergy chain and the minimization of the road-based transport of biomass. The results stress how the optimization of environmental parameters could enhance the mean value of other indicators. In other words, two parameters seem to be important for chain efficiency: the installation of ORC plants and the minimization of transport distances. In the former case, the combination of thermal and electric energy production generally increases the performance of economic indicators and the substitution of fossil fuels compared with other typologies of plants. A positive impact is also shown for the reduction of the risk of negative profit, in particular for the energy plants. The reduction of distances from supply to demand of bioenergy could both improve economic efficiency and decrease the annoyances caused by road-based transport. The application of incentives to support the supply compartment of the wood energy chain is not the most important parameter. However, funds to forest enterprises should be preferred to activate more biomass availability and sustainability of the supply/demand ratio.

The implemented model permits an analysis of the influence of different political and technological choices at the local level, defining the guidelines for a decision of support from local stakeholders. The practical application of the results could be depicted in the potential analysis of added value of the chain due to particular regulations or funds. Furthermore, the risk of employment losses can be evaluated at the enterprise or provincial level. The questionnaires and the GIS-based approach applied for the definition of the input geodatabase allow a rather simple update of supply and demand quantification.

The spatial representation of output provides the opportunity to show the best allocation of biomass in terms of both provenance (distance) and quality. In fact, sawmill residues are generally

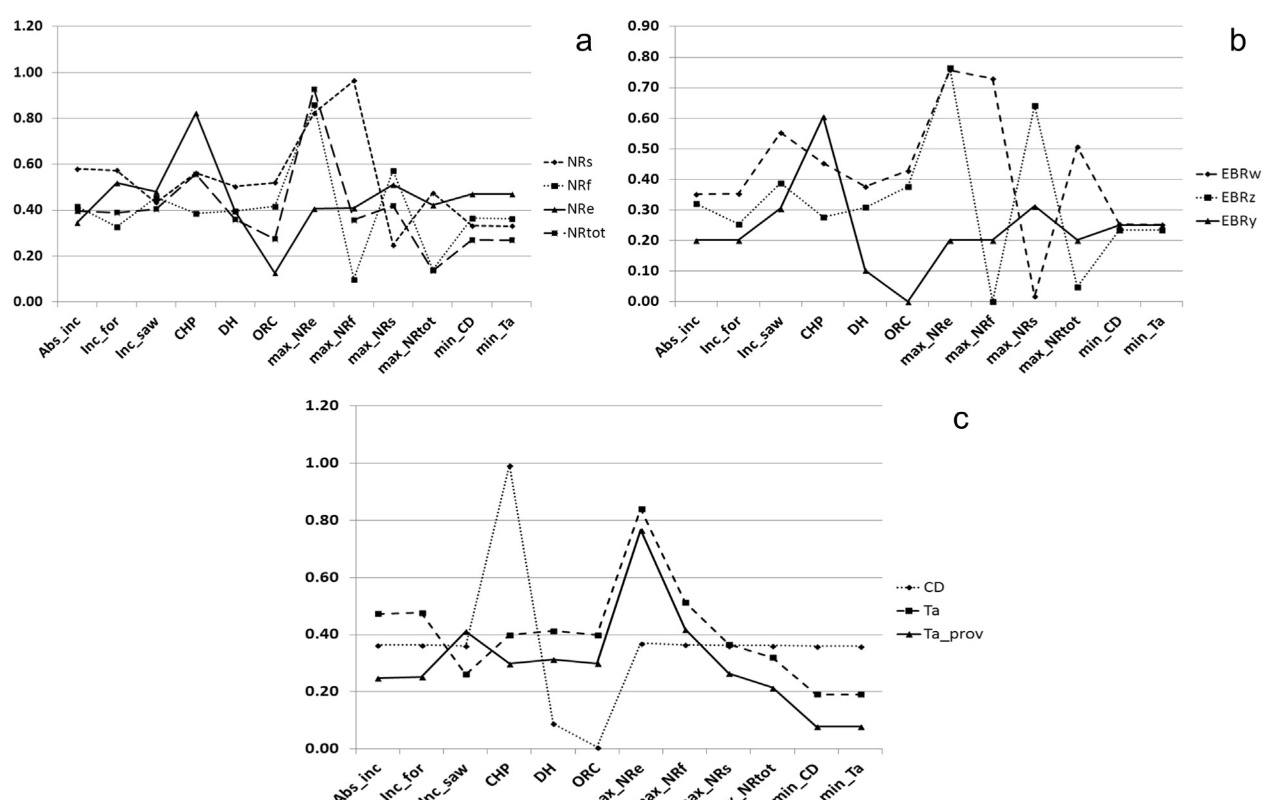

Fig. 4. Trend of indicators based on scenario parameters (distance from ideal point for economic – a, social – b, and environmental criteria – c).

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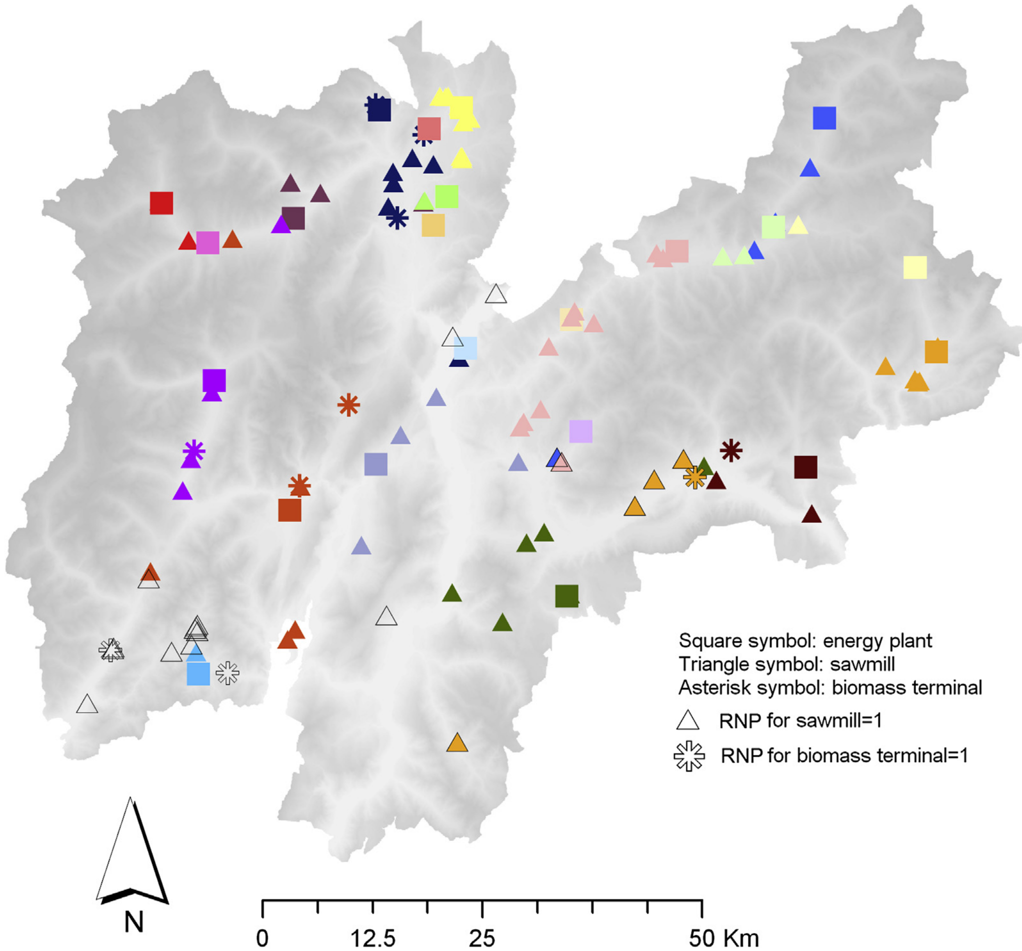

Fig. 5. Best allocation of biomass in scenario "Inc$_{for}$-ORC-min_Ta" and the respective risks of negative profit.

preferred because of the lower levels of impurities and green matter compared with forest residues. However, a larger energy plant (greater thermal power) could facilitate the combustion of forest biomass or biomass with higher moisture content. A geographic visualization of biomass allocation could facilitate the medium-term pledge and agreement among local entrepreneurs; indeed, one of the critical topics of the current local bioenergy chain is the absence of a qualitative analysis of residues and the medium- to long-term agreement between supply and demand. These facts lead to supply/demand agreement based on empirical evaluations, not on standardized rules. Furthermore, market price fluctuations could make biomass plant feeding risky in the absence of supply/demand agreements.

The flexible model structure potentially facilitates the implementation of a new scenario, e.g., in terms of different incentive policies, typologies of plants or allocation of biomass.

Several improvements to the analysis could be depicted as follows. Biomass terminal localization has been hypothesized in a suitable industrial area; according to upcoming regional regulations (Zampieri et al., 2011), BTs could be implemented in a rural area, allowing an optimization of the storage and management of biomass. In-depth local analysis and specific case studies can improve the current applied indicators, e.g., gaining more insight into the perception of traffic annoyances in the biomass sector. Furthermore, additional indicators, both socio-economic and environmental, could be added to the evaluation. For example, the impact of other GHGs besides carbon dioxide can be quantified. Future detailed evaluations can lead to an improvement of the partial equilibrium model in terms of general equilibrium analysis for provincial and interprovincial markets. Effectively, although the current supply and demand of biomass in the province of Trento are mainly related to sawmill/forest residues and DH plants, respectively, additional compartments could attain a certain importance in the medium term. A provincial analysis could include the computation of biomass from other wood industries or the pruning of permanent crops (vineyards and fruit trees) and the demand from small biomass plants. The conflict between forest woodchip production and bote rights (e.g. in terms of local residents' perception) and a mix of DH, CHP and ORC installations should be included in future analysis. At the interprovincial level, an interesting topic to be developed is the application of Life Cycle Assessment for the different uses of wood residues (e.g., panel and paper production).

Ultimately, the adequate availability of datasets regarding the supply and demand of bioenergy could allow the application of this model for different study areas.

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Nomenclature

W_e	wood energy collected at the *e-th* energy plant (MWh/y)
W_{e0}	wood energy currently collected at the *e-th* energy plant (MWh/y)
ps_p	price of sawmill wood energy in the provincial market (€/MWh)
W_m	equivalent wood energy collected at the *m-th* interprovincial collection point (MWh/y)
W_{m0}	equivalent wood energy currently collected at the *m-th* interprovincial collection point (MWh/y)
ps_m	price of equivalent wood energy in the interprovincial market (€/MWh)
cs	chipping cost (€/MWh)
l_e	distance between the *e-th* energy plant and the *s-th* sawmill (km)
tc_e	transport cost to the *e-th* energy plant (€/MWh km^{-1})
l_m	distance between the *m-th* interprovincial collection point and the *s-th* sawmill (km)
tc_m	transport cost in the interprovincial market (€/MWh km^{-1})
E_e	forest wood energy collected at the *e-th* energy plant (MWh/y)
pf_p	price of forest wood energy in the provincial market (€/MWh)
j_e	distance between the *e-th* energy plant and the *f-th* biomass terminal (km)
tc_e	transport cost to the energy plant (€/MWh km^{-1})
q_f	annualized net present value calculated for the financial cash flow of the biomass terminal (Loibnegger and Metschina, 2010) (€)
$H_{e,n}$	thermal energy produced in the *e-th* plant in the *n-th* year (MWh)
p_g	thermal energy price (€/MWh)
$T_{e,n}$	electric energy produced in the *e-th* plant in the *n-th* year (MWh)
p_t	electric energy price (€/MWh)
C_e	investment cost for the *e-th* plant (€)
$O_{e,n}$	yearly operating and maintenance costs for the *e-th* plant (€)
r	discount rate
α_e	thermal power of the *e-th* plant (MWt)
η_e	thermal efficiency of the *e-th* plant (%)
$h_{e,n}$	yearly operating hours for the *e-th* plant in the *n-th* year (h/y)
ω_e	electric power of the *e-th* plant (MWe)
λ_e	electric efficiency of the *e-th* plant (%)
$M_{e,n}$	maintenance costs for the *e-th* plant in the *n-th* year (€)
$P_{e,n}$	personnel costs for the *e-th* plant in the *n-th* year (€)
CD	avoided carbon dioxide emissions in the entire bioenergy chain (t CO_2/y)
k_H	avoided emissions per heat output (t CO_2/MWh)
k_T	avoided emissions per electricity output (t CO_2/MWh)
δ	emissions due to the chipping phase for sawmills and forest enterprises (t CO_2/y)
γ	emission coefficient for the transport phase (t CO_2/km)
Ta	potential traffic annoyance due to woodchip transport (t CO_2/y)

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