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An optimization model for multi-biomass tri-generation energy supply

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ABSTRACT

In this paper, a decision support system (DSS) for multi-biomass energy conversion applications is presented. The system in question aims at supporting an investor by thoroughly assessing an investment in locally existing multi-biomass exploitation for tri-generation applications (electricity, heating and cooling), in a given area. The approach followed combines use of holistic modelling of the system, including the multi-biomass supply chain, the energy conversion facility and the district heating and cooling network, with optimization of the major investment-related variables to maximize the financial yield of the investment. The consideration of multi-biomass supply chain presents significant potential for cost reduction, by allowing spreading of capital costs and reducing warehousing requirements, especially when seasonal biomass types are concerned. The investment variables concern the location of the bioenergy exploitation facility and its sizing, as well as the types of biomass to be procured, the respective quantities and the maximum collection distance for each type. A hybrid optimization method is employed to overcome the inherent limitations of every single method. The system is demand-driven, meaning that its primary aim is to fully satisfy the energy demand of the customers. Therefore, the model is a practical tool in the hands of an investor to assess and optimize in financial terms an investment aiming at covering real energy demand. Optimization is performed taking into account various technical, regulatory, social and logical constraints. The model characteristics and advantages are highlighted through a case study applied to a municipality of Thessaly, Greece.

1. Introduction

1.1. Background

Numerous studies have been performed to forecast the contribution of biomass in the future energy supply, both at a regional and at a global level [1,2]. All of these studies concluded the fact that biomass usage will be increased significantly in the years to come. However, there is no consensus on the maximum level biomass exploitation could achieve.

One of the most important barriers in increased biomass utilisation in energy supply is the cost of the respective supply chain and the technology to convert biomass into useful forms of energy (electricity, heat, etc.). It is therefore natural that many attempts have been made to date to simulate and optimize a specific biomass supply chain on the understanding that significant cost reductions could originate from more efficient logistics operations. For example, an analytic supply chain modelling for five distinct types of biomass was performed in Ref. [3], which concluded that

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20–50% of biomass delivered cost is due to transporting and handling activities. Similarly, very analytical supply chain simulation models for forest [4], cotton [5] and *Miscanthus giganteus* biomass [6] have been developed. In Ref. [7] the cost of producing energy crops – short rotation forestry – was investigated, using spreadsheet models, focusing mainly on the operations of biomass production, collection and storage. In Refs. [8,9] GIS is employed to calculate the exact transportation distances for supplying specific amounts of energy crop feedstock across a state, taking into account the spatial variability in their yield.

Apart from pure simulation models, optimization has also been used in the relevant literature. A linear programming (LP) optimization model has been utilised [10] to optimize a cost function including the biomass logistics activities between the on-farm storage locations and the centrally located power plant, construction and expansion costs of storage facilities, as well as the cost of violating storage capacity or lost revenue in case of biomass deficit. The authors consider the use of ambient and covered storage and take into account the uncertainty in biomass production levels. A very detailed review concerning modelling tools for biomass supply chain and bioenergy conversion up to the year 1999 can be found in Ref. [11], where the author acknowledges the fact that most models tend to deal with only one aspect of the bioenergy system.

Several authors have included in their biomass supply chain modelling efforts also the bioenergy conversion facility, generating electricity and/or heat. The results from using two biomass-to-electricity conversion technologies, a C/ST (fluidized bed combustion with steam turbine) and G/CC (fluidized bed gasification with combined gas–steam cycle), were compared in Ref. [12], concluding that 56–76% of the total system operational costs are due to the biomass logistics, thus indicating the potential for cost reduction. Similarly, a comparative economic evaluation of various bioenergy conversion technologies was performed in Ref. [13], using a comprehensive biomass-to-electricity and ethanol model (BEAM). In Ref. [14] a detailed cotton-stalk supply chain model that employs an LP optimization for the biomass delivery scheduling was presented. This model was applied for centralized (electricity) and decentralized combined heat and power (CHP) power plant scenarios. A GIS-based model to estimate the potential for electricity production from multiple agricultural residues was developed in Ref. [15]. However, the authors do not focus explicitly on the implications of using multiple biomass sources on logistics and warehousing costs. In a similar vein, a technoeconomic assessment of a biomass power plant is performed in Ref. [16], using a mixture of many biomass types. The authors focused mainly on reducing the biomass logistics costs, and more specifically, on eliminating biomass warehousing needs by performing a two-stage optimization: firstly, the CHP power plant location is determined to minimize the transportation distance and secondly, dynamic programming optimization is employed to identify the optimum biomass fuel mix.

None of the abovementioned models is designed to tackle the most practical problem, which concerns satisfying a currently existing energy demand (electricity and/or heat). Rather, these models mostly aim at determining (and some of them optimizing) the cost of biomass logistics and its energy conversion, while at the same time assuming that the energy generated will be exploited. Nevertheless, this assumption is very optimistic in real life conditions, where it is extremely difficult to find an existing heat or electricity demand that would perfectly match the economically interesting biomass potential calculated by these models. In a practical case, one should first identify a suitable application for the biomass-to-energy facility and then examine the economic potential of exploiting the locally existing biomass types with the objective of satisfying real energy demand. Few models of this kind have been developed, one of them presented in Ref. [17], where a biomass supply chain of two fuels (namely, straw and reed canary grass) is simulated for use in district heating applications. This discrete event simulation model aimed at satisfying a daily average heating demand load and the authors concluded that a 15–20% cost reduction can be achieved when using two biomass types instead of one, due to increased efficiency of the biomass supply chain. A similar approach, but only for one biomass type, was adopted in Ref. [18] to determine an economic energy supply structure, covering existing heating demand with district heating network. The problem was formulated as an MILP (mixed-integer linear programming) optimization using a dynamic evaluation of economic efficiency, and binary operators to determine whether to construct or not a district heating network, a heating plant or a co-generation plant. Finally, a combination of GIS, mathematical modelling and optimization for energy supply at a regional level from forest biomass was recently presented in Ref. [19]. The system in question attempted to partially satisfy locally existing heat and electricity needs. The model developed employs GIS to calculate the transportation cost from all potential biomass collection points to all potential CHP plant locations. Then, optimization is performed regarding the optimal sizing of the power plant (defining which kind of energy to produce for the specific area), and biomass collection and harvesting scheduling.

1.2. *Objectives*

The model presented in this paper aspires to combine various advanced features, to form a practical decision support system (DSS) for investment analysis and optimization of a bioenergy conversion investment. The major characteristics of the model are

1. *Multi-biomass supply chain*. The model is able to incorporate parametrically a large number of biomass types. The outcome indicates, among other results, which biomass types and at which quantities should be selected to optimize the financial yield. The multi-biomass approach leads to increased efficiencies in the biomass supply chain, especially when biomass types with high seasonality are concerned, according to several researchers [16,17,20].
2. *Tri-generation with district heating and cooling (DHC)*. Tri-generation is the generation of three types of energy products, namely, electricity, heat and cooling, from one plant. Recent technological advancements and cost reductions of absorption chillers have made tri-generation more attractive. Tri-generation combined with DHC

network is of great interest for relatively warm climates, because a significant extension of the "operational time window" of such a network may be realized, as opposed to traditional district heating applications. The proposed model is the only model in the biomass-to-energy literature that investigates the attractiveness of tri-generation applications.
3. *Demand-driven model*. The simulation and optimization model's objective is to satisfy a specific heating and cooling demand. Therefore, it is more appropriate for use as a DSS for a potential investor that has identified an energy market and wishes to examine the financial attractiveness of satisfying this specific market with biomass than most of the currently existing resource-focused models.
4. *System-wide modelling and optimization*. Optimization is applied to the whole bioenergy system and not only to one of its constituents, thus ensuring that the global optimum design and operational characteristics for the system are identified.

The DSS presented in this paper aims to provide the investor with optimal answers concerning the following investment issues:

- Which is the best location to establish the biomass-to-energy facility?
- Which is the optimal relative size of the base-load CHP unit and the peak-load boiler?
- Which amount of each locally available biomass type should be used and from where should it be collected?

For the purposes of this study optimality is perceived in terms of investment analysis criteria, which is eventually the main interest of every investor. However, certain technological, legislative and social constraints restrict the set of the feasible solutions from which the optimal one is identified.

2. System structure

2.1. *Problem definition*

An investor, either a private entity or a regional authority, has identified a small- to medium-scale heating and cooling demand that could be fully supplied by exploiting locally existing biomass. The investor wishes to assess the profitability of constructing and operating a bioenergy conversion unit to satisfy this energy demand, motivated partly by the current legislation concerning renewable energy investments in Greece that offers large subsidy on investment.

2.2. *Brief model description*

The model simulates the operation of a system comprising of the biomass supply chain, the bioenergy conversion plant and the DHC network that will supply the final customers with the energy products needed. The decision maker may decide which of the locally available biomass types will be included for consideration in the model. The ultimate objective of the whole system simulation is to fully satisfy the thermal and cooling demand in the financially most efficient manner. Thus the system operates at a heat-match mode. Heat produced by the CHP unit and the biomass boiler may be used for heating purposes or it may be transformed to cooling using absorption chillers. The electricity produced is sold at the national grid at prices that are determined by the Greek Regulatory Authority for Energy (RAE).

The system may be broadly classified into three subsystems: biomass supply chain, bioenergy conversion facility and DHC system.

2.3. *Biomass supply chain*

The biomass supply chain may be further disaggregated into biomass harvesting, loading, transportation, unloading, handling and warehousing operations. A more detailed aspect of the subsystems and their interrelationships follows.

2.3.1. *Harvesting and loading*

The model requires as input the price of biomass including the purchasing and the loading cost. The reason for this assumption is that any kind of biomass may be parametrically included in the model by entering some of the most important characteristics such as density (bulk), moisture (wet and dried), heating value (wet), etc. It is practically impossible though to have information about the various collection and loading methods that may be used in connection to every possible biomass type. Therefore, in order to secure the universality and the flexibility of the model, collection and loading costs are included in the biomass price.

The data concerning the biomass existing in the region examined come from the National Statistical Service of Greece (NSSG). Statistical data have been gathered concerning the total area that each cultivation type occupies in each municipality (which is the highest level of detail available). The data have been processed with GIS software and they have been connected to the longitude and latitude of the centroid of each geographical "parcel", i.e. municipality. Therefore, it is assumed that biomass produced in a specific parcel is available at the centroid of the parcel, for transportation calculations. The area occupied with each cultivation type is multiplied by a biomass yield ratio, which signifies the expected biomass yield per area unit and a residue availability ratio, denoting the percentage of the residue that may be considered available for energy production purposes. These ratios are considered fixed for the whole region examined.

2.3.2. *Transportation*

Transportation is performed by standardized transportation vehicles. The alternative use of farmer-owned tractors and platforms has not been considered, as they may be unavailable for a long period of use. The transportation vehicles required for each time period are contracted from a trucking company. The type of vehicle assumed is truck with trailer, according to Ref. [6], with maximum load 25 tons and maximum volume 120 m^3. The average travel speed is assumed to be 50 $km\,h^{-1}$ loaded and 60 $km\,h^{-1}$ unloaded and it is operated by one driver.

Transportation costs are a function of the transportation distance and the time required for the transportation vehicle to make a return trip. The transportation distance is calculated for every potential location of the bioenergy conversion facility during the optimization procedure, by classifying the available biomass into co-centric rings (annuluses) with user-defined breadth. The transportation distance is then calculated as the radius of the circle dividing the annulus into two annuluses of equal area, multiplied by a tortuosity factor ($2^{1/2}$), similarly to Ref. [17]. Time spent by the transportation vehicle includes, apart from pure transportation return trip time, the loading and unloading standing time. Maximum transportation distance is user-defined and is set to 40 km for the case study. Biomass of each type is assumed to be collected and transported in a linear pattern during its entire harvesting period.

2.3.3. *Unloading and warehousing*

Biomass is transported from the fields immediately to the centralized warehouse which is attached to the bioenergy conversion facility. The warehouse is of closed type, according to Ref. [14]. This layout offers the possibility of drying the biomass using exhaust heat from the bioenergy facility, thus avoiding biomass quality degradation and minimizing the loss of material during storage. For this reason, material loss is assumed to be negligible [10,14].

Unloading is performed by using wheel loaders (hereafter denoted as ‘‘Outside loaders’’) which carrie the biomass into the warehouse. Loaders of the same type are used for biomass handling and movement to the conveyor belt (hereafter denoted as ‘‘Inside loaders’’) that transfer the fuel to the adjacent power plant. The simulation model calculates the appropriate number of inside wheel loaders and their number is rounded towards infinity. The inside loaders are purchased and owned by the bioenergy facility and any excess capacity is used for moving the biomass from the transportation vehicles to the warehouse. When this is not adequate, extra loaders are contracted only for the period that biomass is available for collection. The same type of loaders is assumed to be able to handle all potential biomass types with only minor attachment changes. For this reason, the investment cost of the loaders is increased by 10%. Each loader is operated by one driver.

It is assumed that the warehouse will always hold a minimum safety stock to ensure that biomass will have dried adequately before it is used and to avoid a potential unreliability of the bioenergy conversion facility towards the final DHC customers due to fuel shortage.

2.4. *Bioenergy conversion plant*

The bioenergy conversion plant consists of a centralized base-load CHP unit and a heat peak-load biomass boiler. Heat generated may be used for district heating purposes as well as for district cooling using absorption chillers. The relative size of the CHP unit and the boiler is not pre-defined, as is the usual practice in similar cases, but is calculated by the optimization module taking into account several constraints. The inclusion of a biomass boiler is a necessity for numerous reasons: it can cover peak heat loads with low investment cost and it may additionally serve as a backup heat supplier in case of an unexpected damage in the base-load unit. Moreover, the boiler may generate the heat required even when the base-load unit is out of commission for maintenance. Therefore, a higher reliability of the system towards the final heat and cooling customers is ensured.

An important issue arising is the implications of the multi-biomass approach adopted by the model, on the technology of the biomass CHP plant. It is a fact that the various existing bioenergy conversion technologies present a different ability to handle biomass types with varying characteristics. Some technologies are more flexible in biomass characteristics variation (e.g. fluidized bed combustion) as opposed to others (e.g. pyrolysis), and some types of biomass have very similar characteristics whereas others may have totally different. Since in this model every biomass type may be parametrically inserted, it is assumed that the user of the model will have the responsibility to choose the appropriate biomass conversion technology that will be tolerant enough to the characteristics variations of the biomass types under consideration, and he will keep this in mind when determining and inputting the investment, operational and maintenance cost of the CHP plant.

An electricity transmission line is constructed from the CHP plant to the nearest grid connection point. The transmission line is assumed to be a straight line between the two points, which is normally the case.

2.5. *District heating and cooling system*

The absorption chillers are installed at the bioenergy conversion facility. They operate with heat from the CHP unit and/or the biomass boiler and they are chosen among commercially available models. Each chiller is connected to its own cooling tower to allow independent operation – for increased efficiency in partial load. The capacity of the bioenergy conversion plant is determined by the maximum of heating or cooling demand load, taking also into account the DHC network losses.

The DHC network to be constructed consists of a double pre-insulated steel pipeline (forward and return); therefore, it cannot accommodate simultaneous heat and cooling transfer. As a result, the periods of heat and cooling demand must not overlap and consequently this type of network is suitable mainly for space heating and cooling applications, where simultaneous need for heat and cooling is rare. However, the model is easily customizable and may accommodate other applications, like industrial process heat or cooling, even when the two types of energy are needed simultaneously.

The pipeline is designed for the maximum medium flow, either cold (8 °C) or hot water (up to 120 °C). It is therefore obvious that the cooling capacity of a certain pipe is significantly lower than its heating capacity for the same medium flow. The pipeline is assumed to be a straight line between the bioenergy conversion facility and the customer location, which is usual in this type of pipelines. Apart from the main pipeline, a distribution network needs to be constructed if domestic space heating and cooling applications are considered.

3. Optimization model

The simulation and the optimization model were developed in Matlab© by Mathworks.

3.1. Optimization variables

The independent variables that describe the system and are determined by the optimization method are the following:

- P_{MT}: the thermal capacity of the base-load CHP plant (MW). The electrical capacity of the plant (P_{ME}) is proportional to the thermal capacity, as a fixed power-to-heat ratio (PHR) is assumed.
- P_B: the thermal capacity of the peak-load biomass boiler (MW).
- Xb_i: the total amount of the ith biomass type to be procured each year (tons of wet biomass).
- VW_0: the initial yearly biomass inventory (m^3). This variable is necessary, as the calculations are based on a rolling horizon framework, similarly to Ref. [10].
- X_{PL} and Y_{PL}: the optimum location (geographical coordinates) to construct the bioenergy facility (km).

3.2. Objective function

The objective function to be maximized is the net present value (NPV) of the investment for the project's lifetime. NPV was chosen not only because it is the most frequently used investment appraisal criterion in co-generation plant investments [21], but also as it is considered theoretically superior to other criteria [22]. The model calculates also the values of other investment criteria for the optimum solution found (IRR, pay back period), but the optimization process is based on NPV.

The NPV function to be maximized is

$$\begin{aligned} NPV = {} & (R_E + R_{EP} + R_H + R_C + R_G)\mathrm{Df} \\ & - I_W - I_M - I_B - I_{ET} - I_{DH} - I_C \\ & - (A_{BP} + A_{BT} + A_W + A_M + A_B + A_{ET} + A_{DH} + A_C)\mathrm{Df} \end{aligned} \tag{1}$$

It should be noted that the objective function calculates the NPV before taxes. All the annual monetary amounts are multiplied by a discounting coefficient Df, which turns them into present values:

$$\mathrm{Df} = \frac{1 - [1 + (i - \rho)/(1 + \rho)]^{-N}}{i - \rho} \tag{2}$$

where i is the interest rate, ρ is the inflation rate and N is the investment lifetime.

3.3. Revenues of the facility

The revenues of the facility presented here are all in annual amounts. R_E is the revenue from net electricity sale to the grid:

$$R_E = C_E(1 - n_E)\left(\sum_{t=1}^{T} E_{MEt} - E_{DC}\right) \tag{3}$$

where $E_{ME} = E_{MT}PHR$ is the electricity produced, E_{DC} is the electricity consumed in absorption chillers' operation, n_E is the electricity transmission losses and $t = 1,\ldots,T$ is the time period.

R_{EP} is the electricity capacity availability reimbursement:

$$R_{EP} = 12sC_{PE}P_{ME} \tag{4}$$

where $s = 0.9$ for biomass and C_{PE} is the income from capacity availability (€/kW).

R_H is the revenue from heat sales:

$$R_H = C_T \sum_{t=1}^{T} E_{HDt} \tag{5}$$

where C_T is the price of selling a thermal kWh and E_{HDt} is the heat demand of the customers in each time period t. C_T is proportional to the price of oil, as oil is in most cases the competitive fuel that the potential customers will be currently using. Even if they are using another fuel, e.g. natural gas, it is always the case that its price will be connected to the price of oil. In this model it has been assumed that heat will be sold to the customers at a price 20% lower than the respective price of oil.

R_C is the revenue from cooling sales:

$$R_C = C_C \sum_{t=1}^{T} E_{CDt} \tag{6}$$

The price C_C of a cooling kWh is assumed to be 0.036€, when the respective variable cost of producing it using normal electric compression chillers for a typical household in Greece was calculated to be in the range of 0.036 and 0.05€. E_{CDt} is the cooling demand of the customers in each time period t.

R_G is the revenue from GHG emissions' reduction trading:

$$R_G = (G_E + G_T + G_C)C_{CO_2} \tag{7}$$

where G_E, G_T and G_C are the GHG reductions achieved from net electricity produced and from substituting heat produced by oil and cooling produced by electricity, respectively. C_{CO_2} is the market price of a ton CO_2 equivalent.

3.4. Expenses

3.4.1. Biomass supply chain-related expenses

A_{BP} is the annual biomass purchasing and loading cost:

$$A_{BP} = \sum_{i=1}^{n} Xb_i Bpr_i \tag{8}$$

where Bpr_i is the purchasing and loading cost of each biomass type $i = 1,\ldots,n$.

A_{BT} is the annual biomass transportation cost:

$$A_{BT} = \sum_{i=1}^{n} \sum_{l=1}^{L} Xb_{il}(C_{TDi}Ltr_l + C_{TTi}Ttr_l) \tag{9}$$

The coefficients C_{TD} and C_{TT} represent the specific transportation cost per unit of transportation distance and per unit of time, respectively. C_{TD} is mainly affected by the fuel cost while C_{TT} by salaries, insurance, depreciation and maintenance costs. Ltr is the trip distance and Ttr is the return trip time, for every distance class $l = 1,\ldots,L$. For transportation calculations, the vehicle capacity V_C is defined as

$$V_C = \min\{V_{CW}, V_{CV}\} \tag{10}$$

where V_{CW} and V_{CV} are the vehicle's weight and volume capacity, respectively.

I_W is the warehousing equipment and loaders' investment cost:

$$I_W = (E_W C_W + I_L) \tag{11}$$

where E_W is the warehouse area (m^2), C_W is the warehouse specific investment cost (€ m^{-2}) and I_L is the warehousing equipment and loaders' investment cost (€).

A_W is the annual warehousing and handling operational & maintenance (O&M) cost:

$$A_W = E_W O_W + C_{VW} \quad (12)$$

where O_W is the warehouse O&M cost as a percentage of investment cost (€ m^{-2}) and C_{VW} is the variable with time warehousing cost (€) (i.e. salaries, handling, etc.).

3.4.2. *Bioenergy conversion facility-related expenses*

I_M is the CHP base-load plant investment cost minus public subsidy:

$$I_M = C_M P_{ME}(1 - S_{MB}) \quad (13)$$

where S_{MB} is the public subsidy on investment for the CHP unit and C_M is the specific investment cost (€/kWh$_{el}$), calculated from the known cost of a certain size unit, by using a scaling function with scaling factor $R = 0.7$:

$$\frac{C_{M\ \text{size 2}}}{C_{M\ \text{size 1}}} = \left(\frac{\text{size 2}}{\text{size 1}}\right)^R \quad (14)$$

A_M is the CHP plant O&M:

$$A_M = O_M C_M P_{ME} \quad (15)$$

where O_M is the annual O&M of the CHP unit as a percentage of investment cost.

I_B is the peak-load boiler investment cost minus public subsidy, using the same scaling function as for C_M:

$$I_B = C_B P_B(1 - S_{MB}) \quad (16)$$

where C_B is the specific investment cost (€/kWh$_{th}$).

A_B is the boiler O&M:

$$A_B = O_B C_B P_B \quad (17)$$

where O_B is the boiler annual O&M cost as a percentage of investment cost.

3.4.3. *Energy supply-related expenses*

I_{ET} is the investment cost of connecting the power plant to the national grid:

$$I_{ET} = (L_C C_{ETV} + C_{ETF})(1 - S_{ET}) \quad (18)$$

where L_C is the length of the transmission line (km), C_{ETV} is the variable investment cost (€ km^{-1}), C_{ETF} is the fixed connection cost (€) and S_{ET} is the subsidy.

A_{ET} is the electricity transmission line O&M cost as a percentage of the investment cost. I_{DH} is the investment cost for district heating and cooling transmission and distribution network:

$$I_{DH} = L_{DH} C_{DH} + N_{HC}(C_{CD} + L_{DN} C_{DN}) \quad (19)$$

where L_{DH} is the length of the main pipeline (m), C_{DH} is the specific investment cost (€ m^{-1}), N_{HC} is the number of district energy customers, C_{CD} is the fixed connection cost per customer, L_{DN} is the average distribution network length per customer (m) and C_{DN} is the distribution network specific cost (€ m^{-1}).

A_{DH} is the district heating O&M cost. In this study it has been assumed equal to electricity cost for pumping, as DHC networks rarely need maintenance and have a long expected service life.

I_C is the investment cost for absorption chillers and cooling towers:

$$I_C = (N_{CH} P_{CH} C_{CH} + N_{CH} C_{CT})(1 - S_C) \quad (20)$$

where N_{CH} is the number of absorption chillers required, P_{CH} is the cooling capacity of each chiller (kW) and C_{CH} their specific investment cost (€/kW). C_{CT} is the specific investment cost for cooling tower, connected to the capacity of the chiller, and S_C is the public subsidy on cooling equipment.

A_C is the O&M of the chiller and cooling tower, expressed as a percentage of the respective investment cost. The electricity required for their operation is subtracted from the gross electricity generated by the base-load CHP unit.

3.5. Constraints

Several constraints have been introduced in the mathematical formulation of the problem.

3.5.1. *Energy demand constraints*

The heat produced each time period by the base-load CHP unit and the peak-load boiler must satisfy the thermal energy demand of the DHC customers.

$$E_{MTt} + E_{Bt} \geq E_{DTt}, \quad t = 1, \ldots, T \quad (21)$$

where $E_{MT} = P_{MT}\Delta t$ and $E_B = P_B \Delta t$, Δt being the duration of each time period. E_{DT} is the demand for thermal (and cooling) energy at the bioenergy plant's side, taking into account losses.

The abovementioned constraint applies to the average thermal energy demand and production within a time period. Therefore, in order to ensure that the bioenergy conversion unit will be capable of satisfying also the thermal peak loads, another constraint is introduced

$$P_{MT} + P_B \geq P_{DTmax} \quad (22)$$

where P_{DTmax} is defined as the maximum thermal (or cooling) demand of the customers for a pre-defined confidence level (e.g. 99%).

3.5.2. *Warehousing constraints*

The biomass safety stock in the warehouse is set as the amount of biomass adequate for at least 20 days of full-load operation for both base-load and peak-load units.

$$VW_t D_{WM} LHV_M \geq \left(\frac{P_{MT}(1 + PHR)}{n_{Mtot}} + \frac{P_B}{n_B}\right)\Delta t_{20}, \quad t = 1, \ldots, t \quad (23)$$

where VW_T is the volume of the biomass inventory at the end of each time period t (m^3), Δt_{20} is the 20-day period, D_{WM} is the mean density, LHV_M is the mean lower heating value of the biomass mix to be used and n_{Mtot} and n_B are the total efficiency factor of the base-load and peak-load unit, respectively.

Another constraint is introduced, due to the rolling horizon of the model: The finishing season stock (VW_T) must be at least as much as the starting season stock (VW_0).

$$VW_T \geq VW_0 \quad (24)$$

In case VW_T is larger than VW_0, the difference can be interpreted as material loss. However, the application of optimization leads practically always to equal starting and ending period inventory.

3.5.3. *Legislation constraints*

The legislation in Greece requires that a co-generation project may receive subsidy on investment only if at least 65% of the heat generated is exploited:

$$\sum_{t=1}^{T}(E_{HDt}) \geq 65\% \sum_{t=1}^{T}(E_{MTt} + E_{Bt}) \tag{25}$$

3.5.4. *Social constraints*

Specific social or environmental conditions may prohibit the installation of the bioenergy conversion facility in some regions. For example, the bioenergy conversion plant may not be located very close to the DHC customers, which will probably be an inhabited area, due to local opposition [23,24]. For the case study, it is assumed that the bioenergy conversion facility must be located at least a safety distance (L_S) away from the customers' location (X_{HD}, Y_{HD}).

$$(X_{PL} - X_{HD})^2 + (Y_{PL} - Y_{HD})^2 \geq L_S^2 \tag{26}$$

3.5.5. *Logical constraints*

All the independent variables are required to be non-negative. Furthermore, upper bounds are also defined for many of them. For example, Xb_i is bounded by the maximum available biomass quantity of type *i* in the region under examination and X_{PL} and Y_{PL} use user-defined upper and lower bounds, as long distance DHC is inefficient: for the case study, bounds of ± 10 km from DHC customers' location have been introduced.

3.6. *Optimization method*

Optimization is a huge field of operational research and there exist numerous optimization methods. Some of them are applicable only to specific types of problems, whereas others are generally applicable. However, even those ''generic'' optimization methods are usually more efficient when applied to specific kinds of optimization problems.

In the bioenergy supply chain literature, several optimization methods have been applied. Linear programming, a method that has the advantage of simplicity and assurance of identifying the global optimum, has been used [10,14]. These two models managed to retain linearity of the model as the optimization concerned only the biomass supply chain and not the whole system. MILP was used in Ref. [18] to include binary operators for investment decisions in the variables. In Ref. [16], dynamic programming has been used to identify the optimum fuel mix for a biomass CHP unit. However, optimization does not apply system-wide.

As the model presented in this paper aims at modelling and optimizing the entire bioenergy system, non-linearity has inevitably been introduced, thus excluding LP from the candidate optimization methods. Most of the currently existing non-linear optimization methods have the disadvantage that they cannot ensure the identification of the global optimum of the problem.

In order to overcome the limitations of using a specific non-linear optimization method, a hybrid method is applied in the model. This means that firstly, one optimization method is employed to define a good solution to the problem. This solution is used as the starting point of the second optimization method that bears the task to enhance further the solution found at the first step.

The optimization method used for the first step is a genetic algorithm (GA). GAs have been applied for a great variety of optimization problems and are based on the principles of genetics and natural selection. A GA allows a population composed of many individuals to evolve under specified selection rules to a state that maximizes the selected criteria [25]. Some of the advantages of a GA include that it optimizes even non-linear, non-continuous and non-differentiable functions with continuous or discrete variables, it doesn't require derivative information, it simultaneously searches from a wide sampling of the cost surface and it deals with a large number of variables. Even more importantly, a GA may succeed in finding the global optimum due to the fact that the method evaluates simultaneously a large population instead of a single point for most non-heuristic optimization methods. These advantages are intriguing and produce stunning results when traditional optimization approaches fall miserably [25].

A disadvantage of a GA is that, despite the fact that there is a good chance of finding a solution close to the global optimum, the method advances very slowly after a certain point, especially for complex problems. For this reason, a sequential quadratic programming (SQP) optimization method is applied at the second step to define the optimum. This type of continuous optimization methods presents the advantage of very fast convergence. Its disadvantage is mainly the fact that it may identify a local optimum instead of the global, and that the results may be disappointing if one does not use a good starting point. However, having defined a very good solution in the vicinity of the global optimum using the GA, the application of the SQP method with the GA optimum as its starting point may lead to identification of the global optimum with high accuracy.

4. Case study

The model presented has been applied to the case study district of Thessaly, Greece. Thessaly is the largest plain in Greece, and there exist many types of cultivations, thus providing an ideal candidate to apply the multi-biomass concept. The heat and cooling customer is the local community of Farkadon. The objective is to install a multi-biomass conversion facility that will operate on heat-match mode, using real statistical biomass availability data. The amount of biomass existing in the region is obviously very large compared to the needs of the small- to medium-size bioenergy facility under investigation. However, one should be careful not to set the potential bioenergy facility location close to the edge of the area for which we have entered the biomass availability data, as the model would interpret the lack of data as unavailability of biomass and would avoid locations close to the edge. The characteristics of the biomass types considered are presented in Table 1 and the parameters used in the case study are presented in Table 2.

5. Results and discussion

The application of the model to the case study area of Thessaly provided us with the optimal solution that can

Table 1 – Characteristics of five dominant biomass types in the case study area considered.

	Wheat straw	Corn stalks	Cotton stalks	Olive tree prunings	Almond tree prunings
Residue yield (tons/ha)[a]	2.97	5.47	7.17	2.82	6.21
Residue availability factor (%)[a,b]	15	30	70	90	90
Exploitable residue (tons/ha)	0.446	1.641	5.02	2.538	5.59
Moisture wet (%)[a]	20	50	20	35	40
Higher heating value (MJ/dry kg)[a,b]	17.9	18.4	18.1	18.1	18.4
Availability period	July	October–November	October–November	December–February	March
Residue price (€/ton wet)[c]	40	10	10	15	15

a Source: Ref. [15].
b Source: Ref. [16].
c Residue price includes purchasing and loading cost, prices assumed.

be seen in Table 3. Judging by the investment analysis criteria calculated for the optimum solution, the specific investment seems to be very attractive. It is interesting to note though that the optimum solution requires that only a small amount of wheat straw and no corn biomass is utilised. The explanation for this preference of the model is that wheat straw is the most expensive biomass type available but has a significant advantage due to its collection period, whereas corn stalks have very high moisture and are therefore displaced by cotton stalks that are available during the same period.

The location of the bioenergy conversion facility is also of crucial importance. Fig. 1 represents the potential NPV contour for the whole area examined and was obtained by forcing the model to perform optimization for every set of geographical coordinates within the search area. The shaded circle denotes the proximity constraint to the DHC customers. It can be validated by Fig. 1 that the model has suggested the most financially advantageous location for the bioenergy facility, laying by the proximity constraint boundaries in order to minimize the DHC investment costs and energy losses. The investor may also use Fig. 1 to identify alternative locations for locating the facility.

A justification for the financial attractiveness of the investment project may be revealed by investigating the income sources (Table 4). Despite the fact that electricity is the main income source, contributing 44.9% of the total income, it is obvious that district heating and cooling is responsible for the good results. Income from heat is about double compared to income from cooling, the main reason being the high prices of heating oil assumed in the model (0.5€/kg), driven by the

Table 2 – Major case study technical and financial data assumptions.

Technical data	
Electrical efficiency of CHP unit (%)	29
PHR	0.518
Total efficiency of CHP unit (%)	85
Thermal efficiency of biomass boiler (%)	80
COP of absorption chillers	0.7
Financial data	
Interest rate (%)	8
Inflation (%)	3
Investment lifetime (yr)	20
Transportation and handling equipment lifetime (yr)	7
Subsidy on bioenergy facility investment (%)	40
Subsidy on DHC network and equipment (%)	40
Subsidy on electricity transmission line (%)	0
Electricity selling price (€/kWh)	0.06842
Power availability reimbursement (€/(kW × month))	1.58
Heat selling price (€/kWh)	0.0478
Cooling selling price (€/kWh)	0.036
Oil price (€/kg)	0.5
Capacity of reference CHP unit (MW_{el})	2
Specific cost of reference CHP unit (€/kW_{el})	2000
Capacity of reference biomass boiler (MW_{th})	1
Specific cost of reference biomass boiler (€/kW_{th})	200
Scaling factor for CHP unit and boiler	0.7
O&M of CHP unit (%inv. cost/yr)	7
O&M of biomass boiler (%inv. cost/yr)	3
DHC data	
Number of DHC customers	500
Average length of distrib. network/customer (m)	10
Longitude (X position) of DHC customers (km)	333
Latitude (Y position) of DHC customers (km)	4382

Table 3 – Optimum solution and major investment analysis results.

Optimization results	
P_{MT} (MW_{th})	3277
P_{ME} (MW_{el})	1697
P_B (MW_{th})	1144
Wheat straw (tons)	139
Corn stalks (tons)	0
Cotton stalks (tons)	6038
Olive tree prunings (tons)	1481
Almond tree prunings (tons)	1969
VW_0 (m^3)	1897
X_{PL} (km)	331.6
Y_{PL} (km)	4380.4
Investment analysis	
NPV (€)	8,428,793
IRR (%)	0.2745
Pay back period (yr)	5

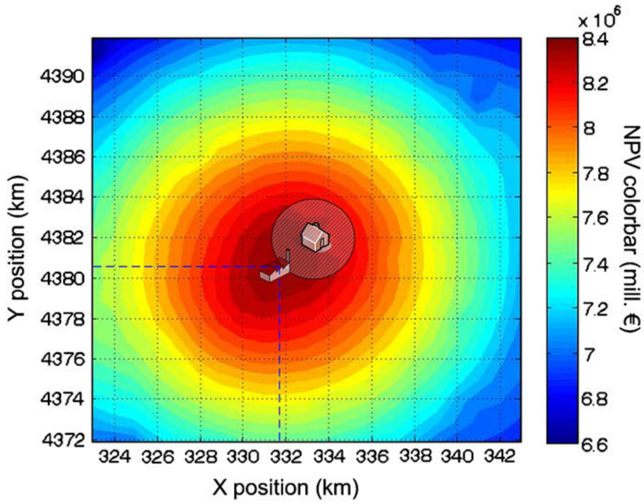

Fig. 1 – NPV contour diagram of the case study area.

worldwide increase in oil prices, as well as the low electricity prices for domestic applications (including cooling) in Greece. It should be noted that income from Greenhouse Gas reduction has not been included, as renewable energy projects located in Greece are not eligible for CDM (Clean Development Mechanism) emissions' trading scheme.

Table 5 presents the project's cost breakdown, from which some very interesting conclusions may be drawn. First of all, it is apparent that transportation costs are extremely low. This happens because of the small mean travel distance (Table 6), owing to the relatively small size of the bioenergy conversion facility, and the, respectively, high biomass availability in the region examined. Table 6 reveals that olive and almond tree prunings are purchased even from relatively long distances, as they offer the major advantage of extending the supply chain operational window, therefore minimizing the share of capital costs and reducing warehousing space requirements. The importance of extending the operational window is more apparent when one notices that biomass warehousing and handling costs account for 19.2% and 8.7% of the total cost, respectively. The high warehousing cost can be attributed to the assumption of using closed warehouses.

The sensitivity analysis performed for the parameters that are not defined by the investor's decisions is presented in Fig. 2. It is interesting to note that the interest rate is the parameter with the highest inverse effect on financial attractiveness of the project, followed by the bioenergy facility investment cost and the operational and maintenance cost. Surprisingly enough, biomass purchasing cost seems to have the least effect on the NPV of the investment. The cause is that mostly low-cost agricultural residues have been chosen to be utilised, and therefore the NPV is not very sensitive to small absolute variations in biomass prices.

On the other hand, an increase in electricity prices seems to be the most augmentative parameter for the NPV, followed by the oil price. This result was expected judging by the relative contribution of electricity and heat income. It is worth mentioning that oil price increase has a dual effect: on the one hand it increases income from district heating, while on the other hand it increases biomass transportation and handling fuel costs. It is obvious by the sensitivity analysis that the former overwhelms the latter by far. Subsidy on investment has a small effect on NPV compared to the other parameters. However, the absolute figures are still important, as a 30% increase on subsidy level results in 8% increased NPV.

6. Conclusion

The model presented in this paper aims to serve as a DSS, focusing at investigating and optimizing a bioenergy supply chain and conversion facility with the ultimate target of satisfying existing energy demand in the financially most efficient manner. The method adopted presents some innovative characteristics, such as combining analytical biomass logistics

Table 4 – Income breakdown.

Source	Income present value (million €)	Percentage (%)
Electricity	9,097,958	43.0
Electric power availability	402,263	1.9
Heat	7,653,528	36.2
Cooling	3,983,958	18.8
GHG	0	0.0

Table 5 – Cost breakdown.

	Cost present value (million €)	Percentage (%)
Biomass purchasing and loading	1.44	11.3
Biomass transportation	0.18	1.4
Warehousing	2.44	19.2
Handling	1.10	8.7
Bioenergy conversion unit investment	2.27	17.9
Bioenergy conversion unit O&M	3.57	28.1
Electricity transmission	0.17	1.3
DH network	0.84	6.6
Cooling equipment	0.70	5.5

Table 6 – Biomass purchased from every distance class (tons wet).

Distance class (km straight line)	Wheat straw	Corn stalks	Cotton stalks	Olive tree prunings	Almond tree prunings
0–4	139	0	6038	0	6
4–8	0	0	0	0	0
8–12	0	0	0	21	98
12–16	0	0	0	8	49
16–20	0	0	0	14	136
20–24	0	0	0	119	1517
24–28	0	0	0	1037	164
28–32	0	0	0	282	0

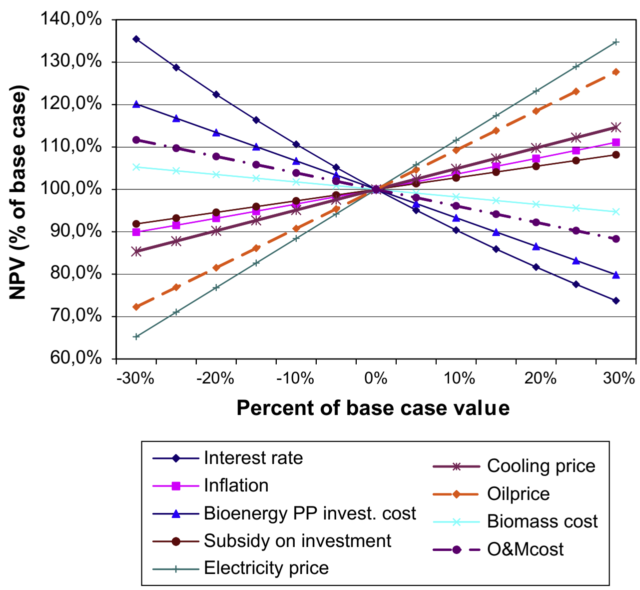

Fig. 2 – Sensitivity analysis.

calculations with holistic bioenergy system modelling and optimization. The system concerned includes the option of tri-generation for district heating and cooling applications. Furthermore, the model is capable of handling multi-biomass scenarios, therefore defining the financially optimum biomass mix for the application examined. A hybrid optimization method is employed for the system-wide optimization to overcome the limitations introduced by the combination of analytical logistics modelling and system-wide optimization. This method has the advantage of defining the system-wide optimum solution.

A case study has been presented to demonstrate the inherent capabilities of the model. The case studied is a tri-generation application at a municipality of the region of Thessaly, Greece, which is based on statistical data for the biomass available in the region. The model provides the optimum bioenergy conversion facility size and location, as well as the biomass mix to be utilised. The results obtained provide ample visibility to the potential investor concerning the details of the optimum design of the facility and the fuel supply chain, as well as the sensitivity of the investment on a set of investment parameters.

As a proposal for further research, it would be interesting to investigate the effect that low-cost storage options would have on the investment analysis appraisal. However, one should take into consideration the respective material losses and quality degradation issues, as well as reduced efficiency of the bioenergy facility due to increased humidity of the fuel. Furthermore, incorporating the effect of uncertainty in the model presented would be a challenging task.

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