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# Integration of biomass into urban energy systems for heat and power. Part II: Sensitivity assessment of main techno-economic factors

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ABSTRACT

The paper presents the application of a mixed integer linear programming (MILP) methodology to optimize multi-biomass and natural gas supply chain strategic design for heat and power generation in urban areas. The focus is on spatial and temporal allocation of biomass supply, storage, processing, transport and energy conversion (heat and CHP) to match the heat demand of residential end users. The main aim lies on the assessment of the trade-offs between centralized district heating plants and local heat generation systems, and on the decoupling of the biomass processing and biofuel energy conversion steps. After a brief description of the methodology, which is presented in detail in Part I of the research, an application to a generic urban area is proposed. Moreover, the influence of energy demand typologies (urban areas energy density, heat consumption patterns, buildings energy efficiency levels, baseline energy costs and available infrastructures) and specific constraints of urban areas (transport logistics, air emission levels, space availability) on the selection of optimal bioenergy pathways for heat and power is assessed, by means of sensitivity analysis. On the basis of these results, broad considerations about the key factors influencing the use of bioenergy into urban energy systems are proposed. Potential further applications of this model are also described, together with main barriers for development of bioenergy routes for urban areas.



## 1. Introduction

Heat energy can be produced very efficiently from biomass and deliver significant carbon savings, and over half of the renewable heat supplied to buildings across Europe is from biomass [1]. Bioenergy can play a relevant role in the decarbonisation of urban energy systems, and biomass heating is one of the most sustainable options for urban areas [2], economically competitive with fossil fuels when highly efficient processes and smart supply chains are implemented, as described in a number of studies [3–6]. Biomass is a limited resource, with a number of potential end-uses in different market segments (including industry, feed, fibers, and pharmaceutical products) hence the optimal allocation of this raw material should be evaluated case to case, on the basis of energy, environmental and economic implications. Biomass use for energy in urban areas presents several drawbacks, such as transport constraints, air emission levels, space requirements and other logistic issues [7–9]. Moreover, biomass can be converted to thermal energy by local boilers or district heating (DH) systems, eventually integrated with CHP plants. The main factors influencing the profitability of centralized vs local heating plants are the load heating density, urban area texture, existing energy networks and infrastructures and refurbishment networks costs, as reviewed in several studies [10,11]. Other factors, such as subsidies available for bio-electricity systems and baseline fuel costs, have been investigated in literature [12]. In order to increase the profitability of district heating, adsorption chillers can be coupled to furnaces for cooling generation systems, using the heat distribution network to transport both heating during winter and cooling during hot season [13–15].

However, urban bioenergy solutions require a trade-off between centralized large plants and distributed small plants: the benefits of the former being high conversion efficiencies, low emission levels and low specific investment and operational costs; while the latter are advantageous due to reduced space requirements, simplified logistics and transport, and ease of plant location close to the energy end-users.

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Several researches aimed to optimize whole biofuel supply chains, including transport, upgrading and storage [16,17], and others focused on the optimal location and sizing of biomass CHP plants [18,19], spatially-explicit input–output models [20], mathematical modeling approaches integrated with GIS [18,21], or EU wide studies addressing both the biomass supply chain optimization and the competing uses for stationary and transport applications [22].

A number of studies propose linear programming based optimization tools such as MODEST for analysis of district heating systems [23] in urban areas, including the integration of large scale biofuel production facilities for the district heating network of the city of Stockholm and assessing the competing uses of the limited biomass resource in the heat and power vs transport sectors [24], the potential use of natural gas for CHP and district heating in some Municipalities in Sweden [25], or the integration of biomass gasification facilities into existing district heating network with combined production of electricity and/or SNG (synthesis natural gas) [26], including the role of policy support measures to make these investments competitive.

However, as reviewed in [27], most of these approaches are developed specifically for a given bioenergy route, and are not designed to be generic and easily extensible. Most of the studies address separately long-term strategic planning [18,19,28] and short-term operational planning [29,30]. A limited number of researches focus on the interaction between seasonality of biomass supply and energy demand patterns [29], and only one research [31] assesses the specific role of bioenergy in UES and the integrated spatial optimization of biomass conversion plants and transport networks. The opportunities of integration of bioenergy into existing energy infrastructures for urban areas have not been addressed so far, and the problem of optimal location of biomass processing and energy conversion plants has been focused mainly on the biomass supply side with limited attention to the influence of the energy demand.

In [27], a MILP model is proposed, in order to optimize the biomass and natural gas supply chains for urban energy systems, and minimize the total energy generation cost under various logistic, technical and environmental constraints.

The main differences between the previous works and the proposed approach are: this model was designed to be completely generic (and hence easily extensible); it aims to determine the optimal network, sizing and location of biomass processing and conversion technologies and their operation simultaneously, including optimal integration between fossil and biomass based routes.

This paper proposes an application of the model described in [27] to a generic urban area and a comparison of the following options in order to find the minimum cost solution: (i) natural gas and biomass (in the form of wood, chips and pellet); (ii) small boilers and DH; (iii) only heating and CHP. A sensitivity assessment is carried out, in order to evaluate how the optimal bioenergy chains selection is influenced by key factors such as:(i) urban areas energy demand and heat intensity, (ii) city size and texture, (iii) existing energy and transport infrastructures, (iv) baseline energy costs and subsidy mechanisms, (v) transport, logistic and environmental constraints.

The results allow making broad considerations about the perspectives of penetration of biomass for heating and CHP into urban energy systems.

The assumed prices of electricity and bioenergy incentives reflect the Italian context. As regards environmental and planning constraints, these are highly variable at national and Municipality level, and in most cases it is not possible to provide a common framework. On the contrary, the methodology aims to assist regulators to define legal and common frameworks to facilitate the optimal use of biomass. In the following section, the model is briefly described, while Section 3 introduces the proposed application to the generic case studies and Section 4 discusses the main factors influencing the use of bioenergy in urban areas through a sensitivity assessment of selected input parameters. Finally, Section 5 draws the main conclusions about the perspectives of bioenergy for urban energy systems.

## 2. Methodology overview and case study description

The urban energy system (UES) is modeled by a set of resources and a set of technologies that convert them, as described in [27]. The city is divided into a number of unitary cells, each of which can have different input parameters (size, energy demand, suitability for biomass and natural gas imports, storage, processing and energy conversion, environmental constraints). The interconnections among cells are modeled by means of transport networks (truck transport for biofuels, district heating (DH) for low temperature thermal energy, gas network (GN) for natural gas). The model determines how best to satisfy the thermal energy demand through the provision of technologies in various zones and networks to transport resources (biomass and natural gas).

The environmental implications of bioenergy routes are taken in account through the assessment of $CO_2$ER ($CO_{2\text{-eq}}$ emission reduction), PM ($PM_{10}$ emission) and PES (primary energy saving) of bioenergy in comparison to baseline scenarios.

The main variables that are determined by the optimization method are: (i) the monthly biomass and natural gas consumption in each cell, (ii) the number of processing plants and conversion plants for each cell, processing and conversion technology and their operation mode (equivalent operating hours per year), (iii) the DH and natural gas network length in each cell. The general model structure is described in [27].

In order to assess the main factors influencing heat and power generation potential and use of biomass in urban areas, the application to a generic case study is proposed, and a sensitivity assessment is presented. On the basis of the results obtained, broad considerations about opportunities and drawbacks of urban bioenergy are also proposed. Although not referring to a specific city, the proposed application considers an economic framework (i.e. biomass and gas costs, electricity price, incentives and carbon cost) reflecting the Italian context, and a technology characterization (i.e. efficiency, CAPEX and OPEX) reproducing the actual levels of processes development. The proposed application represents the case of a ‘realistic’ city and produces generic conclusions applicable to the energy system design in a broader manner, precisely because is not tied to a specific topology, planning or environmental framework. As a matter of fact, the sensitivity analysis performed on key parameters (i.e. energy efficiency level of buildings, climate conditions, energy demand density, geographical texture as well as the main logistic and environmental constraints), provides the stakeholders with a comprehensive framework of scenarios according to which targeting guidelines, regulation and policy strategies to boost bioenergy in urban areas. In fact, most of the sensitivity scenarios could have been not applicable or relevant when focusing on a specific case study. A case study-based approach would have narrowed the range of the analysis and the model capabilities of casting light on future energy system design policy, decisions and regulations. The main input data of the proposed application are proposed in the following, and further details are described in [27].

### 2.1. Energy demand

The base scenario is composed by 8 urban cells (0.25 $km^2$ size each, 10,000 inhab/$km^2$) and 8 peri-urban cells (1 $km^2$ size each,

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