ESTABLISHING LINKS FOR THE PLANNING OF SUSTAINABLE DISTRICTS

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Abstract

Cities can play a key role in mitigating climate change impacts, as they represent two thirds of the world's energy consumption and greenhouse gas emissions. This paper presents a model-based approach to support cities in the challenge of including energy issues in early stage urban planning. Recognizing that successful planning must rely on highly integrated solutions, this paper aims, through its approach, to better understand and reinforce links between generally fragmented sectors, scales, stages and disciplines.

Considering the planning framework of the Swiss canton of Geneva, the main planning instruments are presented and an in-depth analysis of the urban and energetic goals and constraints is carried out. Linking the disciplines of planning and optimization, a Mixed Integer Linear Programing (MILP) model is formulated to identify optimal energy strategies, as well as to provide insights on the urban layout, distribution and size of buildings. Additionally, this approach aims to overcome one of the difficulties of early stage planning, where information regarding energy is scarce. In this regard the proposed methodology generates building information based on available data and constraints. The simultaneous consideration of multiple scales allows to assess the interactions of building scale decisions with overall district energy supply alternatives. The resulting depiction and quantification of trade-offs should allow planners to anticipate optimal energy system configurations and adapt their plans accordingly.

Keywords:
urban planning; urban energy system; multi-scale; optimization; renewable energy

1 INTRODUCTION

1.1 Context

According to the International Energy Agency, cities represent two thirds of the world's energy consumption and greenhouse gas emissions, considerably increasing the effects of climate change [1]. Urban actors are therefore key in reducing overall impacts from cities, in particular by focusing on the building sector. Indeed, in the European context, 40% of the total final energy consumption is from buildings [2]. Urban planners have a significant part to play in the challenge of developing low carbon cities, as one of their main tasks is that of a mediator: to coordinate multiple actors and balance a wide range of often conflicting interests [3, 4]. Historically guided mainly by socio-economic values, current urban planning must as well consider eco-system sustainability [4, 5]. Previous works revealed that considering the energy supply system just in a second step could lead to worse system designs [6, 7].

1.2 Goals of this work

First, within the context introduced above, this paper presents a model-based approach to provide support in the challenge of early stage local urban planning. Considering the planning framework of the Swiss canton of Geneva, an in-depth analysis of the main urban and energetic goals and constraints was carried out. Reflecting as closely as possible this context, though with the aim of extending and generalizing its use to other cities, a Mixed Integer Linear Programing (MILP) model is formulated and applied to identify optimal energy strategies, as well as to provide insights on the urban layout, distribution and size of buildings.

Second, realizing that successful planning must rely on highly integrated solutions, this paper aims, through its approach, to better understand and reinforce links between generally fragmented areas:

- The first link is sectorial and concerns the need for effective methodologies which bridge energy planning requirements with urban planning frameworks [8, 9].
- The second link is between scales. The reliability of planning is increased by recognizing that decisions both on district and building scale mutually depend on each other [6, 10, 11].
- The third link is more practical, dealing with a dichotomy between the strategic phase of planning where uncertainty is high and available information scarce, with the subsequent operational phase which requires and contains more detailed, quantifiable information [12].
- The fourth link is between two disciplines, planning and mathematical programing. The application of the latter may provide highly valuable practical outcomes for planners, but require a fine understanding of the existing planning context and challenges [13].

2 MATERIALS AND METHODS

To achieve the goals stated above, a methodology was adopted, which combines the synthesis of key planning documents and discussions with planners, with the simultaneous development of a MILP model (Figure 1). The workflow begins with a general question, which can be redefined according to insights provided by the outcomes of the optimization phase.

2.1 Planning framework synthesis

Description of case-study

The proposed approach was applied to a green-field urban development site located in Geneva. Originally identified over a decade ago as a suitable urban development site, a rural zone has been modified in 2011 to receive a mixed-use district, including residential, office, commercial and public buildings.

Regarding energy, the project aims to meet the 2000 watts society targets, which includes covering 75% of energy supply with renewable energy sources (RES) [14]. In addition, it is envisaged to become a positive energy district, by exploiting in priority local resources, as well as synergies between activities. The main energy strategies considered in preliminary studies involve geothermal, photovoltaic (PV), and waste heat recovery from the neighboring industrial zone.

Planning framework description

Urban planning can be defined as a tool to ensure a coherent development of the urban space by public action [15]. It is a process which brings together multiple actors from different sectors, connects different scales and administrative levels and seeks to anticipate long-term social, economic and environmental requirements. In practice, planning relies on the use of multiple,

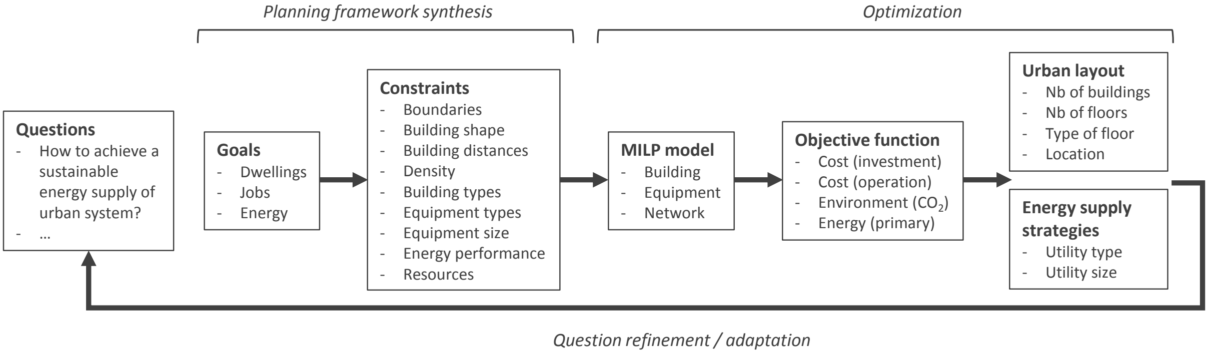

Figure 1. Adopted workflow.

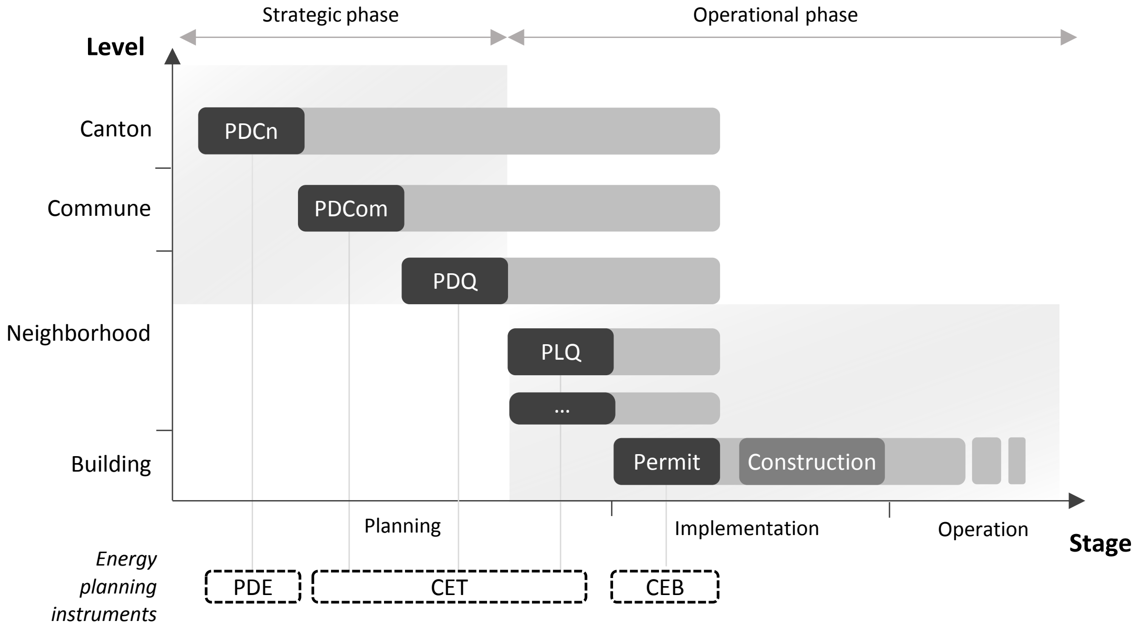

Figure 2. Main planning phases and instruments applied to the Geneva context (see Table 1 for abbreviations).

interacting instruments [16]. These instruments span temporally across different stages, and vertically across different administrative levels. Based on typical planning stages identified by [17] and on the multiple planning levels, the main instruments involved in an urban development project were mapped across these two axes (Figure 2). This process can be divided in two phases, in which instruments serve either a strategic function, or an operational one. We use the term strategic as relating to “a careful plan or method for achieving a particular goal, usually over a long period of time” [18], and operational as in “ready for use” [19] . The strategic phase indeed includes plans and documents which identify long-term goals in a broad range of fields, as well as different possible alternatives. The operational phase extends the general strategies identified in the initial plans, providing local details on the layout of the urban area (e.g. location and size of buildings, infrastructure, public equipment, etc.). The resulting physical plans then lead to building authorizations, construction and, eventually, monitoring, serving for the elaboration of the future strategic plans.

Due to evolutions in the scope of urban planning, which today tends to include the many facets of sustainability [4, 5, 15, 16], the topic of energy is generally present in master plans. However, the extent of its influence on the process, and the methodologies with which it integrates urban planning, if any, are very context specific. The methodology proposed in this paper thus contributes to deepen the understanding of possible synergies between urban and energy planning at the local level. Indeed, as can be observed on Figure 2, the ‘tipping point’ between strategic and operational phases occurs at the neighborhood scale. The dichotomy between the formulation of strategies and the process of their implementation was furthermore identified as a main obstacle for sustainable planning [12]. Regarding energy issues, one of the challenges at this point is to identify and assess meaningful alternatives in spite of missing or incomplete information on buildings or public equipment. Modeling approaches can therefore help planners by providing relevant information, and is a main focus of the paper.

Review of legal and planning documents

To take into account the existing goals and constraints which ultimately influence the development of the considered urban development project, several legal and guiding documents have been reviewed (Table 1). The main urban constraints included density, building heights and minimum distances. Regarding energy, constraints of interest included general efficiency and RES goals, building energy performance requirements and available resources. The information gained in this step could be used to construct the model accordingly.

Because the Cherpines project is still in the strategic planning phase, the localized neighborhood plan (PLQ), as well as the building permits and energy concepts (CEB) were not considered.

Table 1. Main reviewed legal and planning documents

Name	**Type**	**Description**
LGZD	Cantonal law	Development zone law (Loi générale sur les zones de développement du 29 juin 1957)
LCI	Cantonal law	Construction and installation law (Loi sur les constructions et les installations diverses du 14 avril 1988)
RCI	Cantonal regulation	Regulation on the construction and installation law (Règlement d'application de la loi sur les constructions et les installations diverses du 27 février 1978)
LEN	Cantonal law	Energy law (Loi sur l'énergie du 18 septembre 1986)
REN	Cantonal regulation	Regulation on the energy law (Règlement d'application de la loi sur l'énergien du 31 août 1988)
OPB	National ordinance	Ordinance on noise protection (Ordonnance du 15 décembre 1986 sur la protection contre le bruit)
LaLAT	Cantonal law	Application of the federal spatial planning law (Loi d'application de la loi fédérale sur l'aménagement du territoire du 4 juin 1987)
LAT	National law	Spatial planning law (Loi fédérale sur l'aménagement du territoire du 22 juin 1979)
SIA-norms	Norm	Set of standards and requirements for planning and construction in Switzerland. (Société Suisse des ingénieurs et architectes).
PDCn 2030	Cantonal directive plan	Document which coordinates confederation, cantons, and surrounding regions. It sets strategic goals as well as measures to reach them. (PDCn – Plan directeur cantonal).
PDCom Plan-les-Ouates (2009)	Communal directive plan	Document providing a global vision of a commune's development over 10-15 years, coordinating with canton and neighboring communes. Contains a concept and synthesis map, as well as measures to reach the objectives. (PDCom – Plan directeur communal).
PDCom Confignon (2006)	Communal directive plan	Document providing a global vision of a commune's development over 10-15 years, coordinating with canton and neighboring communes. Contains a concept and synthesis map, as well as measures to reach the objectives. (PDCom – Plan directeur communal).
PDQ Les Cherpines (2013)	Neighborhood directive plan	Document depicting a future neighborhood in the mid-term. Sets the projects principles, but not the details of layout and construction. Contains layout alternatives, objectives and synthetic map, as well as measures to reach objectives. (PDQ – Plan directeur de quartier).
PDE	Energy directive plan	Document which sets the energy policy goals on the canton level, and establishes desired shares of energy resources, including RES. (PDE – Plan directeur de l'énergie).
CET Secteur des Cherpines (2011)	Territorial energy concept	Approach and document on the territorial scale which organizes and coordinates actors to reduce energy needs by developing energy efficient infrastructure and promoting the use of local energy sources. (CET – Concept énergétique territorial).

2.2 Optimization model

Simultaneously to the synthesis of the planning framework, and mutually dependent on it, the second part of the adopted workflow consists in optimization to provide answers to identified questions (Figure 1). A computational framework for modeling and optimization of energy systems (OSMOSE) was extended to meet urban specific requirements (e.g. Geographic information system (GIS) interfacing). Within this framework an object-oriented model of urban energy systems was developed which serves to instantiate MILP models for buildings, utilities and networks.

Buildings

The overall density is defined as the sum of floor areas A_{fl} of all buildings per net buildable area of the entire district A_{nb}.

$$ID = \frac{\sum^b \sum^c A_{fl}^{b,c}}{A_{nb}}$$

In order to achieve a specified density, the sum of floor areas over all buildings per usage is constrained by a minimum total floor area per usage :

$$\sum^b A_{fl}^{b,c} \geq A_{fl,min}^c \qquad \forall\, c \in C$$

The floor area per building and usage results from footprint and number of floors per usage:

$$A_{fl}^{b,c} = {n_{fl}}^{b,c} \cdot A_{fp} \qquad \forall\, b \in B, c \in C: c \neq res$$

$$A_{fl}^{b,c} = \left({n_{fl}}^{b,c} + {n_{fl,extra}}^{b,c}\right) \cdot A_{fp} \qquad \forall\, b \in B, c \in C: c = res$$

According to the law, to promote the development of dwellings, the building height limit can be increased, if this floor is used for residential purposes (LCI, **Table 1**). In order to account for mixed used buildings, this constraint is slightly adapted so as to allow extra floors only for buildings which dedicate at least half of the floors to residential purposes:

$$n_{fl,extra}^b \leq n_{fl}^{b,c=res}/2 \quad \forall b \in B$$

The number of floors is limited by the permissible building height:

$$\sum^c {n_{fl}}^{b,c} \cdot h_{fl}^c + {n_{fl,extra}}^b \cdot h_{fl}^{c=res} \leq h_{b,max} + {n_{fl,extra}}^b \cdot h_{b,extra} \qquad \forall\, b \in B$$

The floor height per usage is assumed as the average specific floor height for the existing building stock of Geneva [20].

To calculate annual energy demands and design heating power the area-specific values defined by the MINERGIE-P norm [21] were used (Table 2).

The annual heat and electricity demand per building are thus:

$$Q^b = \sum^c A_{fl}^{b,c} \cdot q^c \qquad \forall\, b \in B$$

$$E^b = \sum^c A_{fl}^{b,c} \cdot e^c \qquad \forall\, b \in B$$

The norms just specify design heating power requirements, but not the according values for electricity. Therefore the design heating power is calculated as:

$$\dot{Q}^{b,t=1} = \sum^c A_{fl}^{b,c} \cdot \dot{q}_{design}^c \qquad \forall\, b \in B$$

A second time step is introduced in order to account for the annual heat demand where the heating power requirement is:

$$\dot{Q}^{b,t=2} = \frac{Q_b - \dot{Q}^{b,t=1} \cdot D^{t=1}}{D^{t=2}} \qquad \forall\, b \in B$$

with $D^{t=1} = 1h$ and $D^{t=2} = 8759h$. Likewise the electric power requirement for all time steps is:

$$\dot{E}^{b,t} = \frac{E^b}{\sum_t D^t} \qquad \forall\, b \in B, t \in T$$

Having these two time steps allows designing the system according to maximum heating requirements and thus having a fair representation of investment costs while also calculating annual operation costs correctly. For electricity needs the sizing step is not as important because at the current state it is assumed that the cantonal/national electricity grid is able to balance any surplus or shortcomings of electricity.

In order to locate the buildings the net buildable area is divided into a regular grid of quadratic cells (see section 3.1). The cell size accounts for minimum distances between neighboring buildings. Each cell can host one building. A building exists only if there are floors:

$$y^b \leq \sum^c {n_{fl}}^{b,c} \qquad \forall\, b \in B$$

$${n_{fl}}^{b,c} \geq 0 \qquad \forall\, b \in B, c \in C$$

This is important to allow the construction of PV cells only on rooftops.

Table 2. Specific energy demand according to MINERGIE-P norm.

floor usage	annual heat demand	annual electricity demand	design heating power
	q	e	$\dot{q}$
	(kWh/m^2/y)	(kWh/m^2/y)	(W/m^2)
residential	30	25	10
office	25	22.2	10

Table 3. Energy technology parameters.

technology	const. cost coefficient	linear cost coefficient	lifetime	efficiency	size	Ref.
	$c_{inv,1}$	$c_{inv,2}$	lt	η	f	
	(CHF)	(CHF/kW)	(y)	(-)	(kWth)	
dec. gas boiler	9124^{lin}	177.1^{lin}	20	0.8	[0, 100]	
cen. gas boiler S	25387^{lin}	50.74^{lin}	20	0.8	[100, 1000]	
cen. gas boiler L	67258^{lin}	14.79^{lin}	20	0.8	[1000, 10000]	
cen. CHP	181670^{lin}	242.8^{lin}	25	0.37 (th), 0.45 (el)	[350, 3500]	
cen. NSHP S	102449^{lin}	408.7^{lin}	20	0.6	[100, 1000]	[31]
cen. NSHP L	258617^{lin}	289.1^{lin}	20	0.6	[1000, 10000]	[31]
dec. GSHP	41864^{lin}	2916.6^{lin}	20	0.43	[0, 100]	
PV	-	4000	20	0.16	-	
dec. HTS	1185^{lin}	15.93^{lin}	15	-	[0, 1000]	[31]
cen. HTS	14130^{lin}	7.01^{lin}	15	-	[0, 125000]	[31]
network pipes	752.8 CHF/m	7047 CHF/m²	60	-	-	

lin: original cost function of author was linearized
dec.: decentralized
cen.: centralized

S: small
L: large

Energy utilities

For a technologic and economic description of all utility models besides of PV it is referred to the work of [22]. All numeric values of utility parameters can be found in Table 3. The electric power generation of PV cells depends on the solar irradiance, electric efficiency and maximum available collector area:

$$\dot{E}^{u,t} = \dot{I}^{t} \cdot \eta_{el,PV} \cdot A_{PV,max} \quad \forall\, u \in U_{PV}, t \in T$$

Considering an available area as defined in [23], only a share of the footprint area can be covered by PV:

$$A_{PV,max} = 0.16 \cdot A_{fp}$$

The factor 0.16 was found to be the average available collector area per building over the building stock of the Canton of Geneva [20].

Heating network

To account for heat losses in the pipes, the distance-dependent temperature model of [24] is adapted.

In order to estimate the investment costs for the network pipes, the overall pipe length is estimated using the formula of [25]:

$$L_{max} = 2 \cdot (n_b - 1) \cdot T \sqrt{\frac{A_{nb}}{n_b}}$$

The number of buildings n_b is assumed to be the number of cells. To account for reduced costs in case not all cells are connected to the network, the maximum length L_{max} is weighted with the number of used heat transfer stations (HTS) at buildings [26]:

$$L = \frac{\sum^{u=HTS} y^u}{n_b} \cdot L_{max}$$

The investment costs for the pipes are then estimated according to [25]:

$$C_{inv} = (c_{inv,1} + c_{inv,2} \cdot d_{ln}) \cdot L$$

Energy target constraints

The 2000 watts society targets of covering 75% of energy supply with RES is formulated as a constraint to the MILP problem:

$$f_{n-RES,grid} \cdot E_{grid,import} + H_{gas,import} \leq (1 - f_{RES,target}) \cdot \sum^{b} (E^b + Q^b)$$

Thus the sum of imported non-renewable electricity and gas may not exceed a specified share of the electricity and heat demand of all buildings.

Table 4. General parameters.

Parameter	Unit	Value	Ref.	Remarks
interest rate	-	0.06	[29]	-
gas price	CHF/kWh	0.0844	[30]	average price for residential building categories
electricity price buy	CHF/kWh	0.2076	[31]	Canton of Geneva, 2015
electricity price sell	CHF/kWh	0.0944	[31]	Canton of Geneva, 2015
external temperature	°C	-7, 12	[29,25]	-
soil temperature	°C	10	[7]	-
annual solar irradiation	kWh/m^2/y	1330	[32]	Geneva, 2014
peak solar irradiance	kW/m^2	1.07	[32]	Geneva, 2014
gas emissions	$\mathrm{kg}_{\mathrm{CO2eq}}$/kWh	0.203	[33]	Switzerland, 2015
electric grid emissions	$\mathrm{kg}_{\mathrm{CO2eq}}$/kWh	0.122	[34]	electricity mix of Swiss suppliers, 2012
share non-renewables electric grid	-	0.433	[34]	electricity mix of Swiss suppliers, 2012
electric grid losses	-	0.09	[35]	-
max. building height	m	21	LCI	-
max. extra height	m	6	LCI	can be allowed for residential floors
floor height residential	m	4	[20], LCI	average over building stock of Geneva
floor height office	m	4.8	[20], LCI	average over building stock of Geneva
footprint	m^2	400	[20], LCI	average over building stock of Geneva
cell size	m^2	900		respects minimum distances as defined by law
minimum density index (ID)	-	1.8	LGZD, PDQ	-
building distances	m	10-20	LCI	street gap between buildings defined relatively to the building heights
design velocity pipes	$\mathrm{m/s}$	2.5	[29]	-
thermal conductivity pipes	$\mathrm{W/m/K}$	0.028	[36]	-
average diameter pipes	m	0.222	[20]	average over heating networks of Geneva
thickness pipe walls	m	0.05	[26]	-
topology factor	-	0.23	[25]	Statistical analysis performed on the heating networks of Geneva
waste heat power	MW	10.75	CET	assumed to be constant over the year
waste heat temperature	°C	20	CET	assumed to be constant over the year
waste heat price	CHF/kWh	0.05	[37]	estimated from current end price of 0.22 CHF/kWh minus investment and operational costs

3 RESULTS AND DISCUSSION

The present study is based on the indicative information available in the current state of the project.

3.1 Case-study application of the MILP model

The values for the parameters considered used are summarized in Table 4. The optimization was performed with CPLEX 12.6.0.0 [27] with a time limit of 300 seconds.

The strength of the model is demonstrated by addressing the fivefold interdependencies between social targets, environmental constraints, economic implications, technological feasibility and urban layout (Figure 3). The costs were minimized for varying densities and RES targets.

As can be seen in Figure 4, there are thresholds above which costs start to increase faster with density. This is due to changes in the technological system chosen. In the first section, fully decentralized systems of ground source heat pumps (GSHP), boilers and PV are favored (Figure 5).

As soon as all cells are occupied, buildings closest to the feed-in point of the industrial waste heat are connected to the heating network (Figure 6). This can be explained with the following observations. For a waste heat price of 0.05 CHF/kWh the optimization model finds the decentralized options to be economically slightly preferable. However,

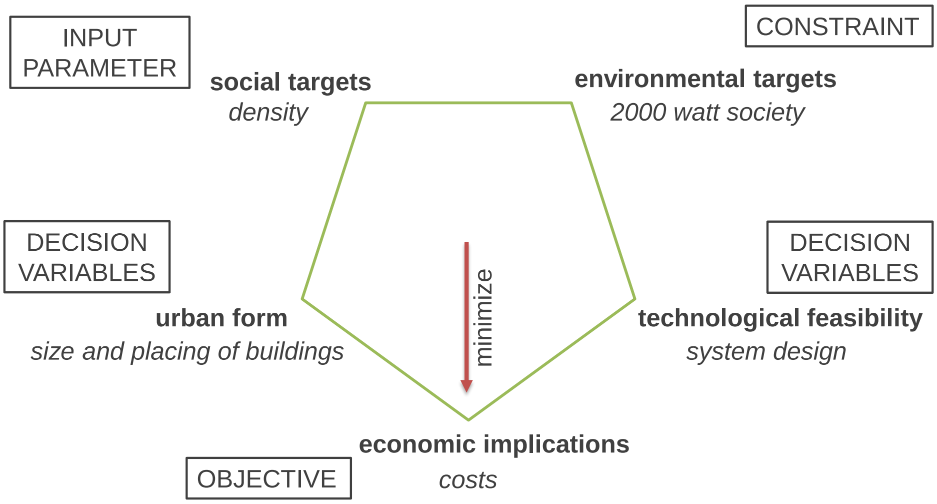

Figure 3. Depiction of the fivefold interdependencies in the optimization problem.

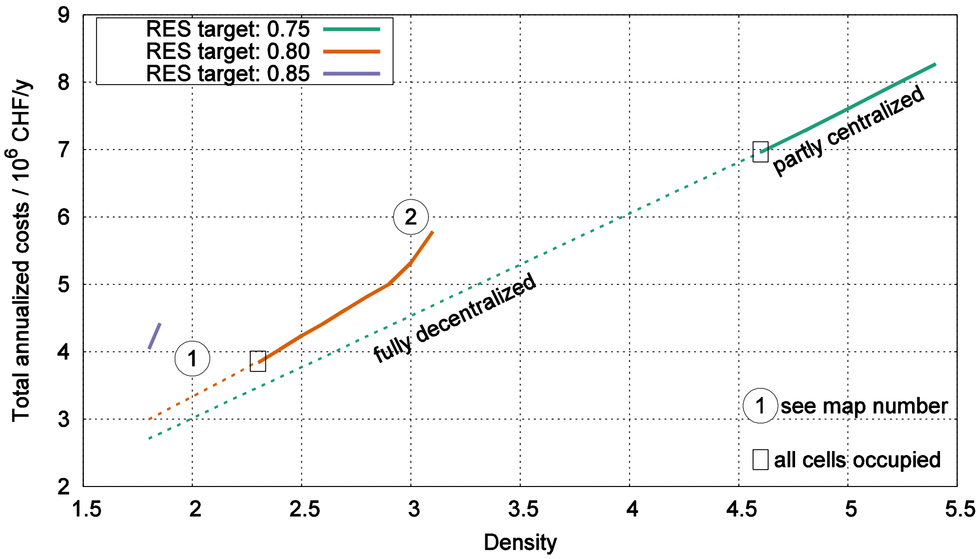

Figure 4. System costs for different RES targets, over varying density. The boxes indicate when all cells host a building. The line style indicates the shift from a decentralized system (dotted) to the use of a heating network (plain). Maps are provided for the numbered points hereafter.

Figure 5. Map of case-study, for a density of 2. The RES target is achieved with a fully decentralized energy supply system, resulting in an overall scattering of buildings.

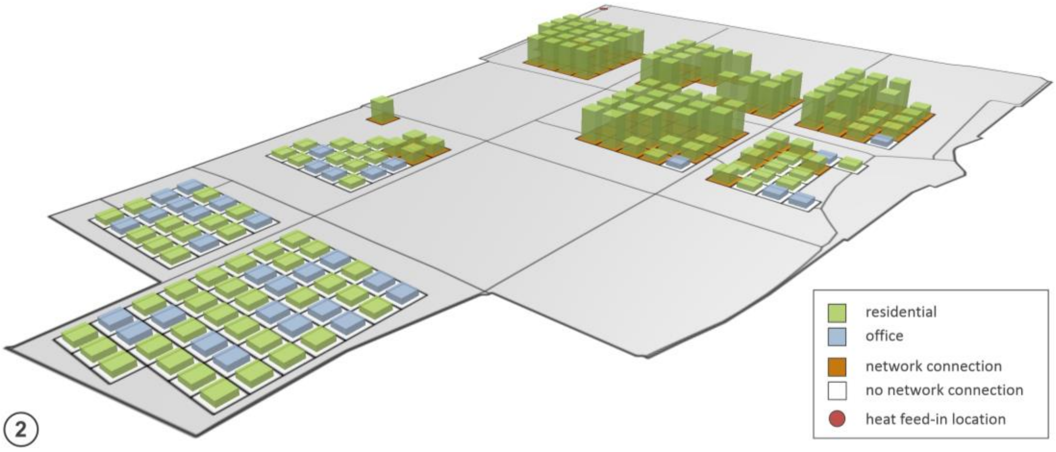

Figure 6. Map of case-study, for a density of 3. The RES target is met by including a heating network. High residential buildings are clustered close to the feed-in point and connected to the network.

already in the decentralized system designs, PV panels are required to meet the RES target. With increasing density, more buildings are built, providing space for additional PV. When all cells are occupied, no more PV can be installed. In order to still fulfill the energetic constraint, the overall system efficiency has to be increased. This can only be achieved by connecting buildings to the network, since a centralized network source heat pump (NSHP) using the industrial waste heat is the most efficient option. The higher the RES target, the lower are these density thresholds.

The main levers in shaping these curves were identified as the achievable share of collector area and the waste heat price. A waste heat price of 0.035 CHF/kWh is found to be the threshold up to which a network is installed even for low densities, regardless of the RES target.

3.2 General results

As stated in Section 1.2, one of the goals of the work was to understand and reinforce links between several separated areas.

- Regarding the first link, the proposed methodology represents a useful way for planners to anticipate effects of their decisions, e.g. regarding density on energy strategies. In this sense, the link may be consolidated with a better understanding of two sides of the planning scope: urban and energy aspects.
- The model-based approach supports decisions simultaneously on the building and the district scale. It thus allows to depict interdependencies between them, which, for complexity reasons, may be difficult to grasp with mere intuition.

- The third link can similarly be improved with a MILP approach, which has proven effective to quickly generate information from which calculations can be performed. This represents an improvement from more general approaches which rely on rough approximations and assumptions regarding the unknown information.
- The fourth link was successfully established, and the planning framework and constraints could be modeled through mathematical expressions in line with legal and practical constraints.

4 CONCLUSIONS AND OUTLOOKS

Stemming from the identification of key planning requirements, the adopted methodology could provide deep insights into how planning decisions are interdependent with energy questions.

A first set of questions could be tackled using an MILP model approach. The presented results illustrated how the choice of a density value influences the cost of achieving energy targets, an energetically optimal urban layout and a corresponding energy supply scenario.

Additionally, required links for improved planning of districts were established. Although the adopted methodology allowed to gain a clearer insight on the nature of these links, additional efforts remain to reinforce them. This includes the ongoing development of the model, as well as the embedding of this work in the framing research project which aims to develop a wide range of urban energy systems simulation tools and decision support methods [38].

5 ACKNOWLEDGMENTS

The authors gratefully acknowledge the European Commission for providing financial support during the conduct of research under the FP7-PEOPLE-2013 Marie Curie Initial Training Network “CI-NERGY” project with Grant Agreement Number 606851. The authors would also like to thank the Canton of Geneva for their fruitful discussions supporting this work.

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