

A MULTI-ENERGY MODELLING, SIMULATION AND OPTIMIZATION ENVIRONMENT FOR URBAN ENERGY INFRASTRUCTURE PLANNING

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ABSTRACT

This paper presents a multi-energy modelling environment developed to simulate and optimize urban energy strategies, with a focus on urban energy infrastructure planning. A multi-scale approach is applied for modelling urban energy networks, considered as the backbone of urban energy infrastructure. This is complemented by the modelling of energy demand to consider the costs and impacts of demand-side measures. The model is also linked to a set of optimization techniques in order to provide answers to urban energy infrastructure planning issues.

Two case study applications follow the presentation of the chosen modelling principles to illustrate the type of answers that can be provided by the proposed modelling and optimization approach.

INTRODUCTION

In the broad context of urban energy planning, infrastructure planning deals with strategic decisions concerning the choice of energy conversion and distribution technologies to supply a city with electricity, gas and heating/cooling services. The main questions to be answered involve the type of large-scale energy conversion technologies, the main energy vectors, the definition of priority areas for different types of district energy infrastructure, the number, type and location of distributed energy generation assets and the time at which investments will be performed. Given the inherent complexity of urban energy systems and the related challenges for decision-making, the planning and operating of urban energy infrastructure requires the appropriate energy modelling, simulation and optimization activities.

Traditional approaches applied mainly by municipal energy utilities and private energy service companies are usually focussed on the supply-side and a single energy domain approach. They rarely consider potential demand-side actions or follow a multi-energy approach, mainly because the aim is to validate a business case which might only be related to one energy vector (e.g. for providing heating or cooling services). However, in a “smart city” context (Haslinger, et al., 2011) and in particular when considering the leading role of local authorities confronted with local climate objectives, there is an

increasing need for considering the costs and impacts of demand-side measures (e.g. building renovation or the increasing presence of electric vehicles) and having a holistic look at urban energy systems (i.e. applying multi-energy approach).

The multi-energy modelling, simulation and optimization environment presented in this paper is currently being produced within CitInES, a collaborative project financed by the 7th Framework Programme of the European Commission. It is being integrated into “Artelys Crystal City” (CITY, 2012), a new decision-support software designed to help local authorities in the definition of sustainable, reliable and cost-effective urban energy strategies, and relies on the commercial software platform Artelys Crystal, already used by major energy utilities for the optimisation of their energy systems.

After discussing the state-of-the art in the field of urban energy modelling, this article presents the methodology adopted for modelling energy demand, followed by the multi-scale approach chosen to model energy production and distribution in urban energy networks. The multi-scale approach makes use of detailed networks models as well as models of those same networks aggregated at a lower level of detail, more appropriate for modelling a city as a whole. The development of these two types of models is illustrated in the case of thermal networks. Finally, the paper presents two case study applications to exemplify the type of answers that can be given with the proposed modelling and optimization approach.

MODELLING PRINCIPLES

This paper presents an innovative energy system modelling methodology for optimizing energy infrastructures through detailed simulations of local energy generation, storage, transport, distribution and demand, including demand-side management. All energy vectors (electricity, gas and heat), usages (e.g. heating, air-conditioning, lighting, electrical appliances and transportation) and sectors (residential, industrial, tertiary, urban infrastructure) are considered in order to draw a holistic map of a city’s energy behaviour. The proposed approach is based on the Transmission Systems Operators supply-demand balance methodology and has been adapted to a more local context.

State of the art

Since energy infrastructure planning has traditionally been a task of energy suppliers and network operators, the tools supporting infrastructure planning tasks have been tailored to the different supply domains (electricity supply, gas supply, heating and cooling supply). The result is a set of tools that handle the specificity of each energy supply domain and that cannot be easily combined to handle multi-energy issues. Multi-energy infrastructure planning questions have rather been handled at a strategic level with the support of tools such as MARKAL/TIMES based on GAMS/CPLEX (Mendes, Ioakimidis, & Ferrao, 2011).

However, when it comes to site-related infrastructure planning questions, such strategic level tools fail in providing the answers expected by the local energy planners employed by the local authorities. Typical questions are related for instance to the choice between energy distribution networks based on different vectors for the supply of new or existing urban areas or the selection of the most appropriate type, location and size of energy conversion plants.

To answer these types of questions arising with the emergence of integrated community energy systems of increased complexity, the past decade has seen a variety of attempts to develop decision-making tools that can assist cities in developing urban energy strategies with a focus on urban energy infrastructure planning. Each development has typically originated from a particular domain and then been extended to other parts of the urban energy system.

Some tools, such as CitySim (Robinson, et al., 2007), originate in the field of building simulation. CitySim is capable of simulating the energy needs of urban districts as well as the distributed generation of energy from renewables and low carbon technologies installed within a district. However, it does not integrate yet the complete set of energy distribution and conversion technologies that is available to the urban energy planner. On the other hand, a focus on a detailed calculation of energy needs in buildings is beyond the scope of urban energy infrastructure planners who also need to consider the complete set of urban energy end-users (building, transport, industrial and urban facility sectors).

As a tool focussing on energy integration techniques, EnerGIS (Girardin, Maréchal, Dubuis, Calame-Darbellay, & Favrat, 2010) includes a GIS interface and can be used for the planning of district heating networks and heating plants (e.g. geothermal heat pumps, combined-heat-and-power plants) based on a characterisation of the heating demand in terms of power capacity and temperature requirements. Since this tool focuses on thermal urban aspects, it cannot be considered as a multi-energy tool yet.

In the field of electricity distribution network planning, modelling activities are applied to ensure that there is adequate substation capacity

(transformer capacity) and feeder capacity (distribution capacity) to meet the load demands. Numerous computer-based methods have been developed to address distribution planning problems. They are usually formulated as decision-making problems with respect to the installation or replacement of new feeders and/or substations, i.e. at the medium voltage level. Option valuation techniques are used for the optimisation of investments, of which one of the most recognized work on the subject is from (Clewlow & Strickland, 2012), where physical assets are represented as a set of financial options. This approach allows optimizing large parks of energy assets but lacks a realistic representation of physical and operational constraints. Finally the Power Systems Laboratory from ETH Zurich has dedicated its research to modelling investments in power networks, with a focus on new generation plants but has also published relevant work on network expansion investments (Krishans, Neimane & Andersson, 1999).

The most advanced multi-energy modelling environment for urban energy infrastructure is the one proposed by (Keirstead, Samsatli, & Shah, 2009). Based on an agent-activity model and a resource-technology network model, SynCity can be applied to optimize the location and size of energy conversion plants within the urban fabric. This also implies the selection of the most appropriate network technologies.

Demand-side aspects modelling

The planning of urban energy infrastructure has to consider all major urban energy end-users. The proposed modelling environment therefore considers the building sector, the transportation sector, the industrial sector and the sector of urban facilities (mainly public lighting, water supply and sewage water treatment). In order to be used for optimizing long-term urban energy strategies, the demand-side models for the four selected end-use sectors have to consider:

- 1) the yearly final energy demand for the different end-uses;
- 2) the nominal power installed for the different end-uses (heating, cooling and electricity supply of buildings, nominal installed power of industrial plants, nominal electrical power installed for sewage water treatment plants, public lighting and pumping stations);
- 3) the distribution of the yearly energy demand in different periods of the year, ideally at a daily and hourly basis (i.e. in the form of load profiles);
- 4) and in the transport sector, the yearly amount of fuel used by the different vehicle categories and the related amount of emissions.

The demand-side models will also need to consider the impact of demand-side measures on 1), 2), 3) and 4) resulting from:

- a) in the building sector: an improvement of thermal building performance (implementation of renovation measures) or a change in occupant behaviour (e.g. following the implementation of smart meters, real-time display interfaces, information campaigns and targeted communication on energy saving);
- b) in the transport sector: a shift in modal split, a redistribution of vehicles per fuel type or a redistribution of vehicles per emission class;
- c) in the industrial sector: a modification of the industry process, a static improvement of energy consumption for a given system, due to a higher energy efficiency or a dynamic management of the energy end-use;
- d) in urban facilities: an improvement of the energy performance of urban facilities (e.g. substitution of lighting systems, energy saving measures in sewage water treatment plants) or load shifting measures targeting urban facilities (e.g. public lighting time management);

as well as consider the operational costs directly and indirectly related to energy end-use in the different sectors:

- i. energy-related costs (in €/kWh) deduced from 1),
- ii. maintenance costs (in €/kWh or in €/kW per year) depending on the type of energy conversion technology,
- iii. annualised investment costs (in €/y).

The energy demand model proposed relies on site-dependent input data as well as on data that can be gathered from international standards and benchmarking studies. The model provides the possibility to take into account building stock description and climate data as site-relevant properties without relying on a detailed physical simulation of the buildings' energy performance (e.g. as in (Robinson, et al., 2007)). Typically, energy performance ratings (yearly energy demand) are known for the different building types in a given climate zone.

In addition to this, the model considers:

- normalized hourly load profiles for typical days. Such profiles can be found in literature or provided by standards (e.g. (VDI 4655, 2008)). A set of profiles is available for different building types and usages (heating, cooling, electricity) and can be extended if more detailed information is provided, for

instance by the local energy utility. The hourly profiles are then applied to obtain a distribution of the daily energy demand during the hours of a day. In the case of heating, this daily heating demand is calculated by relying on energy signature techniques.

- the nominal installed power of the heating system, allowing mainly to take into consideration the adjusted nominal heating power requirements after implementation of thermal renovation measures. Specific design heat loads for space heating and domestic hot water preparation can be found in literature or calculated as well on the basis of energy signature techniques.
- the costs and benefits of demand-side activities, such as thermal renovation measures and behavioural change activities. On the basis of a broad literature review that has been performed, a set of data on the types of measures (investment measures or behaviour change measures), costs, savings achieved, conditions of success and rebound effect is available.

In a similar way, the models for electrical appliances, industry, transport and urban facilities are based on specific energy use data, load profiles, impact and costs of measures taken from literature.

Production and Network Modelling: Multi-scale Approach

Simulating an energy strategy requires to jointly optimize (i) the investment plan, by selecting and dimensioning adequate technologies, and (ii) the management of the selected systems over a long period (about one year). The latter consists in a production cost model, where unit commitment and dispatch decisions are computed for each hour of the year, to minimize global production costs. This allows one to simulate the optimal management of a mix of energy assets with various marginal costs, storage management or load shifting. Hence, optimizing energy infrastructures requires a sharp level of detail, which, if it is combined with a one-year period decomposed in hourly time steps, is responsible for a significant increase in the number of variables. Then, the problem we consider becomes too large to be directly solved by current tools. A temporal decomposition-aggregation approach is therefore to be excluded because of the dynamic link between time steps (due especially to potential storage consideration or load shifting).

The underlying idea of the proposed approach is to build a less detailed model – denoted “aggregated problem” – calibrated with detailed simulations. The principle of the aggregation approach (illustrated in figure 1) is based on network simplification. Let us

define clusters that are aggregations of network nodes. The clusters will then become the nodes of the aggregated network, and its connections are those of the detailed network that are not included in a cluster. The clusters are defined so that network dimensioning constraints (transformer capacity, congested links) are represented explicitly.

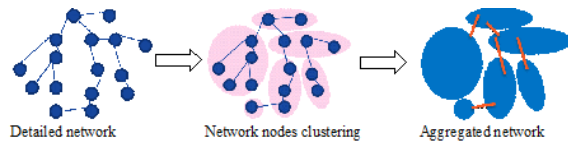


Figure 1 Aggregation principle

After building the aggregated network, we would like to transfer information from the detailed to the aggregated network. While node information could be aggregated by simple operations such as addition, information related to connections (e.g. losses) requires some calibration work. Hence, we build a loss model for each cluster to account for the losses of the aggregated connections. As a result, in addition to line losses, the aggregated network includes node losses. To each energy type is associated a (polynomial) loss function. The function parameters are calibrated based on detailed simulations for well-selected time steps and interpolation. The interaction between the two models is represented on the right side of Figure 2; it implies the following two iterative steps:

1. Disaggregation step: using the aggregated model on the whole study period, compute the optimal production plan/demand-side management policy for each cluster that minimizes the cost of the global system. This may include network reinforcement for explicitly simulated components if it is economically profitable. The resulting production plan and demand for selected time steps are given as input to the detailed simulation to validate/improve the aggregated loss models
2. Aggregation and calibration step: given well selected time steps and corresponding estimated consumption and production, run a detailed simulation and compute losses. If the difference between detailed losses and aggregated losses in each cluster is below a given threshold, exit the algorithm and keep aggregated results. Otherwise, update clusters and loss model calibration and return to 1.

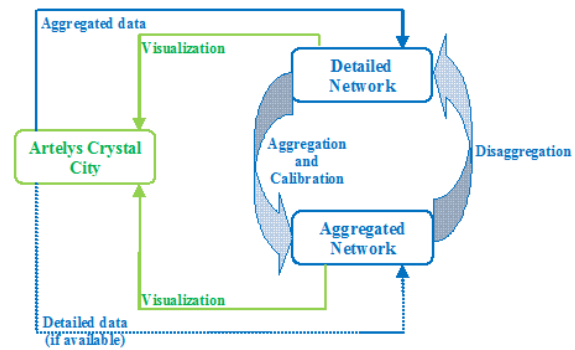


Figure 2 Interactions between detailed and aggregated models.

The Artelys Crystal City tool (on the left in Figure 2) serves both as a central database for all types of energy data and as an ergonomic interface, allowing a global or detailed display of the network).

In the case of new distribution networks, or if local authorities do not have access to data from distribution system operators (DSO), the calibration methodology is replaced by a statistical approach. Aggregated model clusters and loss models are built based on urban characteristics (e.g. density, type of buildings) of the area to be developed. The link between the urban characteristics and the parameters of the model is computed by using data mining techniques on similar urban examples, for which detailed distribution network data is available and previous aggregation methodology has been performed. Network infrastructure costs are also estimated in this way. The “multi-energy environment” use case presented in the last part of the article illustrates this approach.

Let us illustrate the development of a detailed and of an aggregated network model with the case of the thermal network model developed for simulating the behaviour of district heating and cooling networks. Similar approaches have been applied for the modelling of electrical and gas networks.

Thermal network modelling applications

The detailed model is based on a steady state approach, where transient hydraulic phenomena (e.g. impact of supply temperature variations or water hammer) are not included, and is applicable to hydronic district heating and cooling networks as well as to steam networks or ice-slurry networks (with different pressure drop calculations). Due to the number of state variables relevant for district heating and cooling networks and their physical relationships, in first approximation the computations can be performed in two successive steps (see Figure 3):

1. The hydraulic calculation leads to pressure drops and mass flow rates while fixing supply and return temperatures at supply and demand nodes. This allows for

considering pressure driven flows, relevant in case of meshed networks or multiple heating or cooling plants.

2. The thermal calculation is an iterative computation of heat losses in branches and temperature levels at nodes, both for supply and return pipelines.

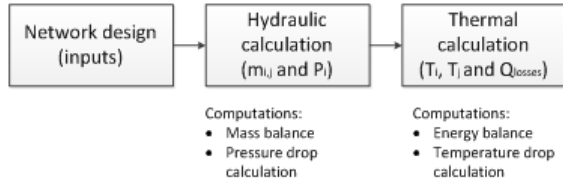


Figure 3 Flow description of the mathematical model

Solving the network distribution problem consists in finding values, at all nodes i , for pressure P_i , mass flow rates s_i , heat losses $\dot{Q}_{losses\ i,j}$ and temperatures T_i solving the following non-linear equations:

- 1) $\forall i \in V, \forall (i,j) \in E$, find P_i and $\dot{M}_{i,j}$ so that:

$$\left\{ \begin{array}{l} \sum_{j \in V} \dot{M}_{i,j} = s_i, \forall i \in V \\ P_i - P_j = f \cdot \left(\frac{l_{i,j}}{d_{i,j}} \right) \cdot \frac{1}{2\rho a_{i,j}} \dot{M}_{i,j} \cdot |\dot{M}_{i,j}|, \forall (i,j) \in E \end{array} \right.$$

- 2) $\forall i,j \in V, \forall (i,j) \in E$, find T_i, T_j and $Q_{losses\ i,j}$ so that:

$$\left\{ \begin{array}{l} \sum_{j \in V} c_p \cdot \dot{M}_{i,j} \cdot (T_i - \Delta T_i) = 0, \forall i \in V \\ \dot{Q}_{losses\ i,j} = u \cdot l_{i,j} \cdot \left(\frac{T_i + (T_i - \Delta T_i)}{2} - t_e \right), \forall (i,j) \in E \\ \Delta T_{i,j} = \frac{\dot{Q}_{losses\ i,j}}{\dot{M}_{i,j} \cdot c_p}, \forall (i,j) \in E \end{array} \right.$$

where the mass flow rate provided (in case of a heating or cooling plant) or used (in case of a consumer substation) at the node i , s_i , is positive in case of a supplied quantity (heat delivered to the supply pipeline in a heating plant or a cooling substation) and negative in case of a used quantity (heat taken from the supply pipeline in a heating substation or a cooling plant). The network design and topology are described by means of two parameters: length $l_{i,j}$ and diameter $d_{i,j}$ of pipeline (i,j) . Only the supply pipelines are explicitly defined. Return pipelines are considered in the computations (calculation of temperature drop and thermal losses). The above set of equations can be solved by using Matlab coupled with a nonlinear optimization solver, namely the *fmincon* function of the Matlab Optimization Toolbox (MATLAB, 2012) as well as the *Knitro* function (KNITRO, 2012).

The aggregated model is based on a simplified network with loss model and thermal inertia. Indeed,

for district heating networks, supply-demand balance does not have to be respected perfectly each hour, which provides some flexibility for network operation. This flexibility is modelled through fictive storage capacity associated with each cluster. These storage capacities are calibrated using the same process: detailed simulation of well selected consecutive time steps, taking into account network operation constraints (pressure and temperature drop) to calibrate the level of flexibility (storage capacity) for the aggregated production management.

CASE STUDY APPLICATION: AN ELECTRIC NETWORK

The test case analysed in this section concerns the analysis of impact of demand-side management (DSM) actions in a smart grid environment. DSM actions are usually designed to influence the energy demand for the mutual benefit of the utility (or distribution company) and its consumers. These initiatives enable the utility to induce changes to the time and demand pattern of electricity usage and improve the cost effective use of the utility's resources, and enable consumers to benefit through reduced energy costs. The load diagram reshaping, with smaller peaks and an overall tendency to become flatter, conveys important benefits to the power system structure in general (improved utilization of energy production and distribution network), to customers (reduced energy costs) and to society (reduced environmental damage resulting from less air pollution and a smaller amount of active generators).

In this study, the effects of DSM are simulated assuming that part of the load can be curtailed and restored later in the same day – load shifting. The possibility of load displacement depends on the will of the customer, but load control is usually focused on air conditioning, heating and refrigeration. The idea is to take advantage of building thermal inertia to disconnect devices for a while during peak periods without causing major discomfort.

The power network model used in this case study was built to represent a typical portion of the city of Bologna, study object of the European Project CitInES (www.citines.com). The consumption distribution per consumer type (residential, industry, commercial and public lighting) as well as the proportion of distributed generation per type, networks characteristics (voltage level, losses, etc.) and environment features (Deliberazione 29 dicembre 2011 - ARG/elt 196/11, 2012) are considered to be analogous to the city distribution. Usually, some types of loads have higher priority over other loads. Particularly for the industrial case, it is assumed that most of the industrial loads are critical and cannot be subjected to load control. Hence, the model for the DSM implemented in this research only considers the possibility of control of a

part of the residential consumers load. Figure 4 shows the consumption distribution provided by the authorities of the city of Bologna in their report (Comune di Bologna - Unità Intermedia Qualità Ambientale, 2007). This distribution was used to define the total controllable load: the aggregation of refrigeration, water heater and heating gives the total controllable load (L_c). As not all consumers adhere the DSM programs, the real controllable load will be a small percentage of L_c (usually between 5% and 10%).

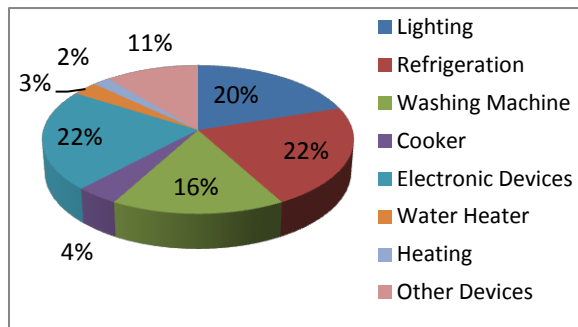


Figure 4 Distribution of electric consumption at low voltage

It was also assumed that load curtailment occurs between 17h and 19h (peak hours) and also that curtailed load must be fully restored within a period of four hours after the power cut. Two strategies were considered in this study:

1. The load is cut between 17h and 20h, and the corresponding energy is supplied within 4 hours on the same day;
2. Similar to case 1 but with the possibility to anticipate certain consumptions.

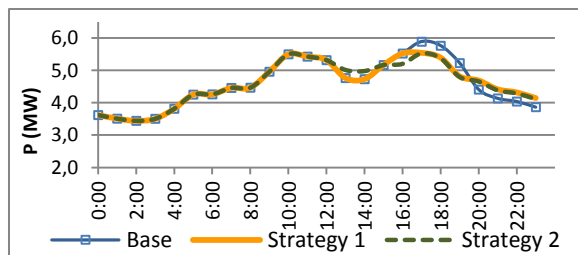


Figure 5 Simulated impacts of DSM strategies 1 and 2 on the measured base load profile

Figure 5 presents the simulation results obtained with for the case of controlling 5% of L_c . The potential of DSM actions led to beneficial load diagram changes. The peak diminishes similarly in both cases (strategies 1 and 2) but the resulting curve is smoother in the second case.

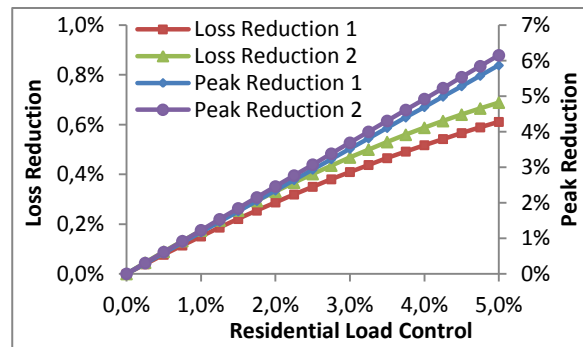


Figure 6 Loss and load peak reductions for different values of controllable load

The peak and loss reductions as a function of controllable load for strategies 1 and 2 are presented in Figure 6 showing comparable results in terms of peak reduction and slightly better results for strategy 2 in terms of the loss reduction. It is important to emphasize that peak reduction is a very important aspect of network exploitation because of the limitations of line capacities. Normally the decisions for the investments to reinforce lines and transformers are made taking into account peak load, i.e. the worst case situation for the network. This analysis therefore shows a possibility of postponing network investments, which in turn may represent a decrease in the (operational and investment) grid costs.

CASE STUDY APPLICATION: A MULTI-ENERGY ENVIRONMENT

A specific multi-energy planning problem was studied in the case of Marne-la-Vallée, a suburban town east of Paris looking into building a new eco-district called "Sycomores". Using the methodology described in this article, the impacts of two different energy plans for the new district have been studied and are presented here.

In the first case (case A), the new district is composed of 4000 individual houses only plugged into the existing electrical network. Each house is equipped with both solar thermal and photovoltaic systems. In the second case (case B), the new district is composed of 4000 flats in 4 storey buildings. A district heating network system, fuelled by wood and gas, guarantees space heating and domestic hot water needs. In both use cases the district is considered as composed of a unique, perfectly homogenous consumer type.

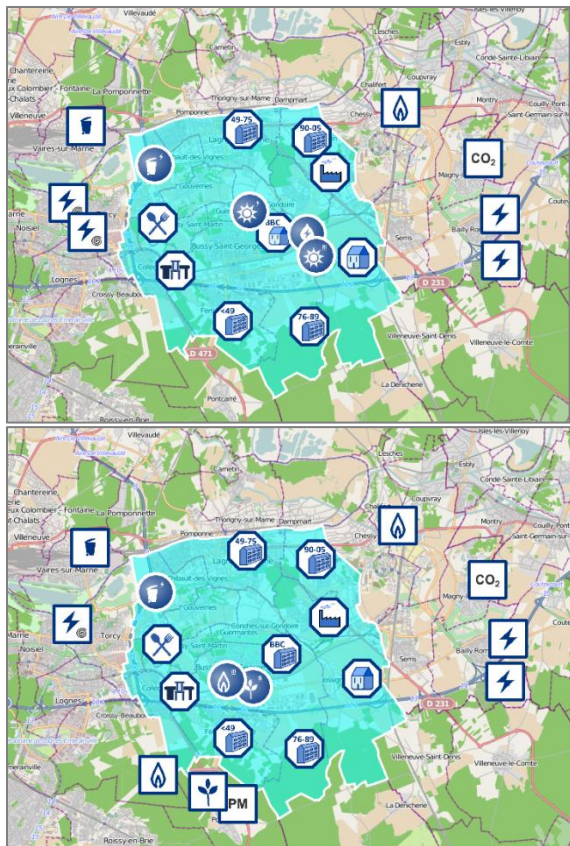


Figure 7 Illustrations of cases A (top) and B (bottom)

Consumption data

In France the total energy consumption of new buildings needs to comply with targets set by the latest national building regulations. These are determined per square meter and depend on the location and altitude of the building, on which energy vector is used to supply the building and whether the building is equipped with an integrated power production installation. The total annual consumption for each end-use of use cases A and B was calculated based on the figures corresponding to the location and altitude of the planned eco-district and to the supply strategy (energy vector and integrated power production) chosen for each use case, multiplied by an average size of 100m² per housing. The resulting total annual consumption for space and water heating, lighting and appliances for use cases A and B is provided in Table 1.

Table 1 Distribution of the simulated annual consumption (MWh/year) for 4000 housings of 100 m² in cases A and B

	Case A	Case B
Space heating	5712	4988
Water heating	1632	1424
Lighting and appliances	8976	7840
Total consumption	16320	14252

The same normalised consumption profiles per needs were used in each case. These profiles come from a

database produced within the CitInES project. A different profile for each use and type of consumer is considered. The total consumption by area is also computed adding local consumption profiles of all consumers and all usages.

Local production data

In case A, it is assumed that houses are one storey high and 20% of the roof surface can be used for solar energy production. Solar energy production installed capacity is determined by available roof surface. All heat produced by solar water heating systems is used for home consumption and extra water heating need is provided by the electricity network. Electricity produced by solar panels installed on the houses' roofs is sold back to the network and necessary energy for space heating and specific electricity needs is bought directly from the electric network. Solar radiation data in Marne-la-Vallée was obtained from the open database (Solar Energy Services for Professionals: http://www.soda-is.com/eng/services/services_radiation_free_eng.php) Data used for solar panels (representing an installed photovoltaic capacity of 5.76 MWp) and for solar water heating systems can be found in Table 2. In-house hot water storage is modelled as a 1MWh storage capacity for all houses.

Table 2 Data for solar PV and solar thermal heating systems

	Solar PV	Solar Thermal
Orientation	West	West
Inclination	25°	25°
Total surface (m ²)	72000	8000
Cell efficiency	100 Wp/m ²	-
System efficiency (%)	80	90
CAPEX (€/MWp/year)	275000	67 CAPEX (€/m ² /year)
OPEX (€/year)	0	0

In case B, it is assumed that space and water heating needs are entirely supplied by a district heating network. Electricity for lighting and appliances is bought directly from the network. Marne-la-Vallée is surrounded by woods that can be used as a potential source of renewable biomass. Base heat need is considered to come from a wood fuelled unit and peak heat is provided by a gas thermal plant.

It is important to note that fuel costs are not accounted in the operational expenses (OPEX), as the total amount of fuel used is being computed. OPEX here refers to fixed running costs. Data used for the urban heating from wood and gas units respectively can be found in Table 3.

Table 3 Data regarding urban heating

	From wood	From gas
Installed	1.2	0.8

capacity (MW)		
Heat yield	3 MWh/tons of wood	0.77 MWh /MWh gas
Emission rate	0.66 tons of PM/MWh	0.2 tons of CO2/MWh
CAPEX (€/MW/year)	25000	5000
OPEX (€/MW/year)	13000	13000

The installed capacity of each heating unit has been dimensioned using optimization techniques. It is assumed that 7km of heating network has to be deployed to supply the new district. Data of Table 4 are used.

Table 4 Data regarding the heating network

CAPEX (€/km/year)	60000
OPEX (€/km/year)	13500
Heat storage capacity (MWh)	2
Heat storage maximum variation (MW)	0.7

Thermal inertia and line losses of the heating network, computed using the multi-scale approach described above, were integrated to the model.

External energy supply data

Data used for external energy supply are similar in both cases. The cost of network electricity used is based on the regulated price applied by EDF, the local provider, for individuals, which varies according to consumption date and hour. Other facility prices (Table 5) are assumed to be constant over time.

Table 5 Facility prices

Gas price (€/MWh)	30
Wood price (€/t)	30
Solar electricity feed-in tariff (€/MWh)	258
Particle matter emission cost (€/t)	10
CO2 emission costs (€/t)	0

Computed results

Energy system optimal operation is simulated over one year. From these hourly results aggregated indicators are computed in Table 6.

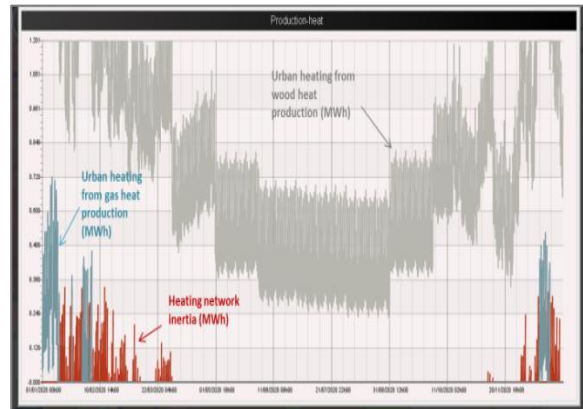


Figure 7 Computed production level (MWh) of heat from wood (grey) and gas (blue) over the simulated year. Thermal inertia of the heating network is an energy storage asset. In red the storage output.

Table 6 Aggregated indicators

	Case A	Case B
Total OPEX (k€/year)	0	120
Total CAPEX (k€/year)	2117	454
Electricity feed-in (k€/year)	(-) 1754	
Gas purchase (k€/year)		4.2
Wood purchase (k€/year)		61
Particles matter emissions costs (k€/year)		40
Electricity purchase (k€/year)	1149	581
Total costs (k€/year)	1512	1260
CO2 emissions (t/year)	1146	785

CONCLUSION

This paper proposes a multi-energy modelling environment capable of supporting city administrations and their counterparts in energy utilities in planning the construction and operation of energy infrastructure within their city. Given the complexity related to combining the different energy vectors of urban energy systems an aggregation-based modelling methodology is used to create an aggregated model of the whole city and its energy distribution networks. Multi-energy tools are then applied to this aggregated model to analyse the impacts of the different energy strategies.

Two case studies illustrate the possible application of the environment. The first illustrates the type of outcomes it can produce when considering a single energy vector, in this case the impact of demand-side management measures on an electricity distribution network. The second, a multi-energy case study, allows the comparison between energy strategies based on different energy vectors, hence answering the multi-energy planning problem encountered by urban planners when designing the development of one city.

NOMENCLATURE

$a_{i,j}$ [m²] = cross sectional area of pipeline (i,j)
 c_p [J/K.kg] = specific heat of water
 $d_{i,j}$ [m] = diameter of a thermal network pipeline between nodes i and j
 E = edges of a network
 $f_{i,j}$ [-] = friction factor of pipeline (i,j)
 $l_{i,j}$ [m] = length of pipeline (i,j)
 $\dot{M}_{i,j}$ [kg/s] = directed mass flow rate in a pipeline (i,j)
 P_i [Pa] = pressure at a thermal network node i
 $\dot{Q}_{losses\ i,j}$ [W] = heat losses in a pipeline (i,j)
 s_i [kg/s] = mass flow rate provided or used at a thermal network node i
 T_i [K] = temperature at a thermal network node i
 t_e [K] = ground temperature
 u [W/m.K] = overall heat exchange coefficient of a pipe
 V = vertices of a network
 ρ [kg/m³] = water density

ACKNOWLEDGEMENT

This work was supported by the European Union within the European Project CitInES (7th Framework Programme, grant 288295).

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