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Multi-energy planning of a city neighbourhood and improved stakeholders' engagement—Application to a Swiss test-case

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Abstract

During the IntegrCiTy project, a novel urban energy planning approach was successfully tested. The latter combines stakeholder engagement with an innovative multi-energy model using different control strategies, while combining both energy demand and supply dynamics on selected zones. The applied control strategies applied to the energy networks show the potential gains linked to using synergies among networks and technologies, as to foster renewable energy penetration in the system.

Thanks to the combined approach of advanced optimization techniques and stakeholder engagement, solutions can be identified much quicker. In addition, unfeasible solutions can be discarded at earlier stages of the planning process, based on the feedback of the stakeholders even though, from a pure mathematical and energy point of view, the solutions might be theoretically interesting to consider.

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1. Introduction & approach

Urban energy systems combine various complexity levels that can be tackled only within a holistic approach. On the demand side, a wider range of energy conversion technologies need to be integrated, such as power-driven heat pumps or co-generation units, considering their mutual interactions and possibly complementary roles (e.g., providing different temperature levels or backup services) [1]. On the supply side, energy distribution networks in urban zones – power, natural gas, and heating/cooling grids – are linked with high investment and operational costs, often entering in competition with other infrastructures using the urban underground, in potentially difficult

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trade-off situations. Finally, from an urban planning point of view, the traditional approach must now take into account more stringent environmental objectives at local and national levels, the willingness of a consistent part of the population to adopt sustainability standards in the built environment, along with new mobility-related constraints. Finally, in the last ten years, cities have turned from energy consumption sinks, supplied by centralized large power plants located on the outside and transport grids, to a myriad of energy-generating hubs by way of rooftop PV plants, biogas-producing wastewater treatment plants and distributed micro-cogeneration units [2].

Hence, urban energy systems analysis and planning must be embedded in an approach that is intrinsically multi-energy and multi-stakeholders. Such a framework must thus be able to consider on a same level all the energy vectors present in a given urban zone – while most studies usually concentrate on only one vector, e.g., low-voltage power or district heating networks – thereby opening the opportunity to identify synergies. The framework must also consider all the involved parties in the layered governance fabric of cities and neighbourhoods, including local authorities, energy utilities but also local self-producing cooperatives or housing associations. The approach presented in this paper hence combines the multi-energy and multi-stakeholders' perspectives within an innovative and original decision-support environment, taking advantage of the latest grid simulation techniques – including co-simulation –, data semantics – such as CityGML – and GIS frameworks [3].

This approach was developed by way of an ERA-NET project called *IntegrCiTy* [4]. Its main objective was to develop a decision-support platform aimed at city planners, as well as local energy providers. The resulting IT platform and embedded tools were subsequently tested in selected cities on well-defined use-cases.

The approach and results presented in this paper stem from the test application of IntegrCiTy platform in the Swiss city of Vevey, in a test-case defined in close collaboration with two industrials partners, namely Holdigaz and Romande Energie. The first objective was to compare the present situation with a proposed energy system, based on a centralized network using water from Geneva Lake as a cold source. A model predictive control was simulated, in order find the best possible use of the different energy resources, including co-generation units. The whole framework was developed on python [5].

2. Methodology: Stakeholder's engagement and decision-support framework

Identifying the right energy planning approach for a given neighbourhood usually represents a difficult task for local authorities and, often, even for energy utilities; indeed, a trade-off must be found between the technical complexity and the practical viability of obtained results of the planning process as well as a political viable scenario development for the future use. Additionally, a broad panel of stakeholders should be integrated in any project [6,7], in order to both increase the political support for the proposed solutions and to gather crucial inputs for the detailed energy planning process. According to our experience, local energy utilities can rely on detailed information related to energy consumption, at least at building level, especially when supplied via a network. Public actors have the task of initiating and driving the energy planning process, according to the legal framework. Finally, industrial plants play a double role, as they are usually characterized by large energy consumption, while also potentially providing often unexploited sources of heat with appropriate waste heat recovery technologies, e.g. as to supply a local urban district heating network.

Finding and agreeing on common goals among different actors is necessary to successfully start the planning process. Starting with a general goal aiming at increasing renewable energy in the system leads to the technical planning questions on how to successfully plan a multi energy system with different stakeholders. Giving space to a broader spectrum of technological options also represents part of the approach, which usually leads to solutions that require more than one energy vector and simultaneously lead to reaching more ambitious objectives in terms of energy efficiency and environmental impact, not to mention financial viability. Moreover, the inclusion of an external stakeholder from a non-profit organization proved to be valuable so that interests of different internal stakeholders such as energy network operators and authorities could faster reach a common formulation of questions. Finally, an emphasis was placed on the identification of the current challenges faced by the stakeholders, in addition to the strong assertion of overarching environmental goals. These challenges were then integrated into the simulation, which therefore turns into a toll aimed at supporting informed and quantifiable discussions, instead of being only a representation of the energy system. Simulation methods allow to set the basis for a successful decision support system that helps advancing towards applicable solutions.

In the selected case study presented here, two main challenges were central to our discussion, in addition to the overreaching goal of increasing renewable energy: The need for a sustainable use of the existing gas network infrastructure and the need for an efficient management of the future electricity demand peaks. Both challenges have informed our modelling questions which are centred on a limited use of the gas network to offload the electricity grid in the framework of proposed energy system, which involves the use of different heat pumps. In simpler words, the role of our simulation is to complement the stakeholder discussions on the usefulness of co-generation units to locally support the electricity grid [1].

In a second step, based on the first set of questions and simulations, concerned stakeholders are integrated into the stakeholder's group that meets regularly to validate the advances within the project. Within this group, energy systems can be chosen, adapted, or invented because the purpose of a method within the process can be clearly defined. Data can be screened ensuring quantifiable answers that can then be more easily compared.

3. Scenario definition

The studied area of the City of Vevey stretching between the railway station and the shores of Lake Geneva — represents approximatively 33% of the city's heat needs, primary energy and green-house gases emissions.

As described in Fig. 1, the chosen concept with the stakeholders combines:

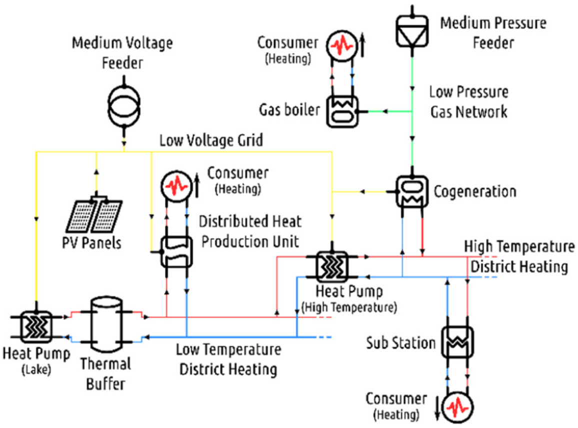

Fig. 1. Proposed multi-technology system. Legends: —: Gas network, —: Electricity network, —: Heating network (Blue: low temperature and red: high temperature)

- medium and low voltage power grids,
- medium and low-pressure natural gas networks,
- a low-temperature district heating network (LT-DHN) based on centralized and decentralized heat pumps using a lake as the main thermal source,
- a gas-fired combined heat and power plant supplying two small scale high temperature district heating networks (HT-DHN).

Two heat pumps considered as consumers on the LT-DHN also supply heat to the two HT-DHN. The power grid and the district heating networks are coupled with the centralized and decentralized heat pumps. The natural gas network is linked to the power grid through the co-generation power plant, also connecting the gas network with the high temperature district heating network.

In the studied area, the buildings with installed heating power above 100 kW correspond to 75% of the total installed heating power. Starting from this observation the buildings selected to be connected to the proposed systems are all characterized by installed capacity above 100 kW. Moreover, buildings with a high heating temperature level (>70 °C) in the low-temperature area have intentionally not been selected to maintain an acceptable coefficient of performance for the distributed heat production units. A more refined calculation will be performed in future projects, in order to take all buildings into account.

The paths of the proposed LTDH, HTDH1 and HTDH2 networks have been generated combining graph theory and evolutionary algorithms [5]. Based on nominal heat consumption values and design parameters, this methodology allows to design the path of a network extracted from road data and the diameters of the pipes.

Fig. 2 presents the application's areas for the proposed concepts:

Fig. 2. Application's areas of the proposed concepts.

- the high temperature networks at East (HTDHN1) and North (HTDHN2)
- low-temperature network between the train station and the lake

4. Estimation of energy demand data

To run the simulation, heating, and domestic hot water production synthetic load profiles at a frequency of 15 min have been generated based on an adaptation of the degree-day's method and on normative values with added randomness. The data used to estimate the present and future energy consumption on the studied area are extracted from three sources:

- The Swiss Federal Register of Buildings and Dwellings (RBD), this register is mainly used to retrieve the information concerning the affectation, the construction epoch of the buildings and the energy agent used to produce heating and hot water. It also provides the reference heated surface of a building, the number of levels and the geographical information about the ground surface and shape of a building.
- The (city-level) mandatory chimney sweep register, this register provides information about the installed power of natural gas and oil boilers, as well as production temperature needed levels and installation year combined with estimated renewal year.
- The static annual energy planning study with [8] based on and combining the two previous data sources. It estimates the future energy demands in terms of heating, hot water, cooling, and electrical services for multiple time horizon at the scale of the parcels.

5. Model

A simulated energy system was partitioned as follow in Fig. 3: heat and electricity demands are gathered into one simulation node for all the buildings. The power grid node is directly affected by the electricity demand. The heat demand is satisfied through connections to the HT-DHNs, gas network and a DHPU (Distribution Heat Production Unit) which composed by a series of parallel heat-exchanger used as substations combined with heat pumps, a stratified thermal storage, and dedicated controllers [5].

The low temperature network along with the two high temperature networks are deployed in three different containers. The two heat-pumps providing energy to the two HT-DHNs are also isolated on dedicated containers.

Based on this design and scenarios presented, a Centralized model predictive control (C-MPC) is applied to limit maximal electrical power use. For the C-MPC operation, the controller has access to all variables and can control all operation variables [9,10]. The single optimization cost function is defined as to minimize the system-wide cost of operation based on a varying cost of electricity taken from EPEX SPOT (day-ahead auction) and a fixed cost for natural gas. System-oriented constraints can be added to the model, for instance a maximum value for the electrical consumption for the external power grid or constraints on the overall operation of natural gas-powered systems (boilers and co-generation plants). The model is solved using the solver Gurobi.

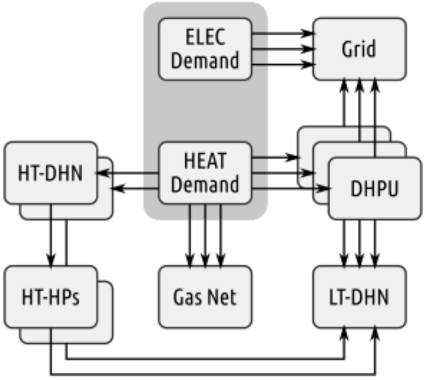

Fig. 3. Partitioning of the studied system for co-simulation.

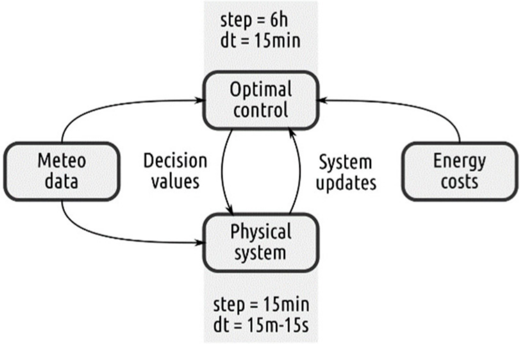

Fig. 4. Integration of the control model into the physical system.

Table 1. Parameters of the main objective function.

Symbol	Unit	Description
$P_{grid-ext}$	kW	Power consumed from external power grid
$P_{ngas-ext}$	kW	Power consumed from external gas network
NG_{cost}	CHF/kWh	Natural gas cost
EL_{cost}	CHF/kWh	Electricity cost
t	Min	Timestep

Fig. 4 describes the integration of the control model into the physical system model within the co-simulation. After every 6 h of simulation, the controller receives an update of the physical system together with the future energy costs and meteorological data to generate the next operating plan. During the next 6 h the physical system continues its co-simulation, exchanging internally data every 15 min and following the updated decision/operation control values. The optimal control model is considered as a simple node in the co-simulation graph, at the same level as a model of a district heating network or a model of a building.

The objective function of the Centralized model predictive control is (see Table 1):

$$\min \sum_{t=0}^{end} P_{grid-ext}(t) * EL_{cost}(t) + P_{ngas-ext} * NG_{cost}. \tag{1}$$

The model also simulates:

- The energy balance of the heat pump, between electrical energy consumed, energy taken from the source and given to the sink.

- The influence of the COP on the electrical energy consumption of the heat pump (fixed COP, pre-computed for each temperature level of the buildings with ambitious hypothesis).
- The influence of the partial load on the behaviour of the heat pump. The value of αmin is fixed to 0.8 for heat pumps between the lake and the LTDH and between the LTDH and the two HTDHN and fixed to 1.0 for all the other heat pumps.

The variation of the storage's mean temperature is determined by the balance between the energy produced by the associated heat pumps and the energy consumed by the building. Without initial or reference value this storage's mean temperature can be seen as an equivalent of a state-of-charge between upper and lower temperature bounds (here respectively fixed at 70 °C and 50 °C). Semi-continuous variables are used to model the partial load of the heat pumps.

6. Results and discussions

Fig. 5 presents the effect of the decision values for C-MPC. The hatched area represents the electrical production, and their sum is subtracted from the total of consumption (cogen: co-generation production, solar: solar photovoltaic production). The light blue part represents the actual electricity consumption. The red line represents the power consumed from the external power grid. All the other values are represented stacked (consumption of the system equipment as hp: heat pump, dhpu: distributed heat production unit).

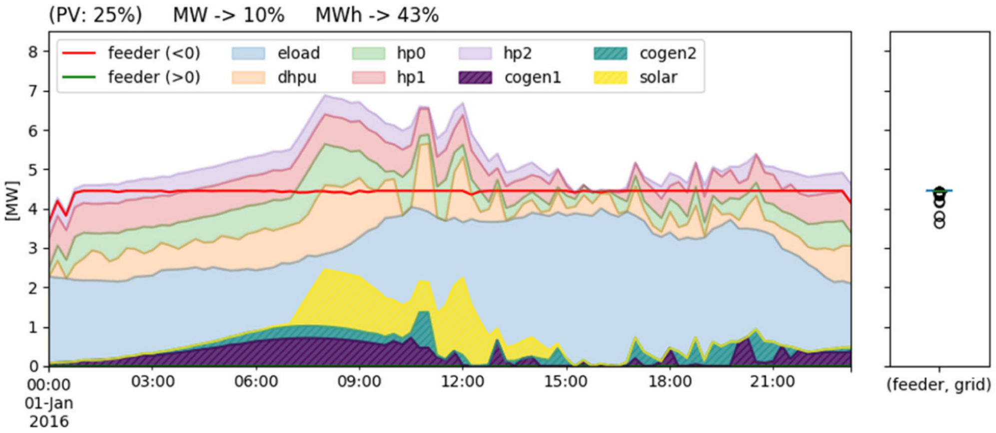

Fig. 5. Total of stacked consumption and the consumed power from the external power grid (feeder).

As can be further seen on Fig. 5, the implemented controller almost manages to flatten the electricity consumed from the external grid, matching the consumption of the heat pumps with the production of co-generation plants and the solar photovoltaic units. We can also see that the centralized control tends to an equilibrium of the heat pumps consumption. This solution can help to optimize the actual power grid but needs to be consolidated according to the technical limitations of the power grid management.

The assumptions for the simulation parameters are given in the following table:

Value	Unit	Description
0.45	–	Yield of the co-generation plant - Electricity
0.4	–	Yield of the co-generation plant - Heat
3.2		COP of the heat pumps in the HTDH
8.0	–	COP of the heat pumps in the LTDH
0.1	CHF/kWh	Gas cost
0.025 to 0.055	CHF/kWh	Electricity costs -EPEX Spot

The stakeholder's engagement dynamics that has been put in place by the IntegrCiTy endeavour has had a profound influence of the evolution of the planning scenarios [6,7]. The initial idea by one of the local energy companies was to build a centralized heat pump system, based on the lake water that would cover essentially all the southern part of Vevey. By including the municipality and another local utility, the project opened up not only to a multi-energy vision that included both natural gas distribution network and district heating, while taking into account the intrinsic limits of the low-voltage power feeders for the selected neighbourhood. Moreover, the developed scenarios automatically took into account the local authorities' objectives in terms of renewables penetration, energy efficiency and GHG emissions, as new solutions emerged such as the separation between LT- and HTDH.

Key factors to the development of such a constructive framework were also linked to a broad work on the harvesting and structuration of the energy demand and the early work with stakeholders. Since, for the chosen urban zone, available data was integrated and validated down to single building level, it has been possible to match energy supply scenarios as precisely as possible to the present reality, as well as to evaluate future expected evolutions of the building stock taking into account refurbishment rates. With such a level of detail, all stakeholders could also bring in their development projects, as they usually develop them, on a building level, in order to ask for a construction permit.

7. Conclusion

In conclusion, the case study of Vevey allowed to design an energy system scenario which offers links the three types of energy distribution systems: distribution power grid, natural gas network and district heating networks. This test case shows the potential gains of optimizing control for the efficient management of a local multi-energy network and system.

Built on problem-based learning, the approach combines a holistic energy-system analysis with a multi-stakeholder integration for cities down to neighbourhoods. It considers different energy and environmental objectives. Compared to existing approaches that often only concentrate on the energy system analysis, key actors are included from the beginning in the decision-making process. The iterative approach then ensures considering all constraints, soft ones coming from the actors as well as hard one linked to physical limitation. On the IT side, the tool combines georeferenced information with an open-source system architecture that can connect existing tools via a common message broker system.

A clear perspective emerging from this work is given by the difficulty to involve all stakeholders in using a decision-support tool with advanced technical features, that are not easily accessible without specific knowledge. Urban energy planning will indeed become a more complex task, since the spectrum of technology options widens, while energy efficiency requires putting in place rather complex operational strategies. Hence, solving this paradox between the need to broaden up stakeholder's engagement, while aiming at adopting largely non-trivial technological strategies will represent an important challenge to be tackled in future evolutions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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