Territorial energy systems:
A methodological approach and case study

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ABSTRACT:

Energy transition emphasizes the role of local authorities towards a sustainable future: energy productions are increasingly more decentralized by valuing renewable energies often rooted in territories. Management and operation of local energy systems are becoming more complex due to this paradigm shift (grid and supply/demand balancing), especially because production and consumption are not synchronized and not spatially related (temporal and spatial discontinuity).

Territorial energy systems approach, consisting in analyzing all energy aspects of a territory in an integrated and simultaneous way (needs, resources, conversion and storage technologies), provides a relevant answer to this issue. It allows to systematically consider a large number of solutions, different by nature, in term of energy vectors and technologies, and to compare them in term of global performances at a territory scale.

Nevertheless, it requires a very large amount of data to be structures and secured, as well as powerful calculating algorithms, combining energy and information technology (IT) aspects: smart cities and smart grids.

Moreover, a territorial energy approach helps to provide actual answers to local entities, mainly through informatics tools, in term of energy monitoring and planning. Some of these tools will be highlighted through concrete examples.

KEYWORDS:

Territorial energy system; energy system simulation and Optimization; energy planning help decision tools; territorial energy data; multi-energy networks; smart cities

1 INTRODUCTION

Energy challenges facing our society have led to the definition of major common objectives, such as energy efficiency promotion, optimal use of local and renewable energy resources or greenhouse gas emissions reduction, considering current logic of overall growth.

Main streams that allow to achieve these common objectives within a territory are linked to energy demands reduction, equipment and energy conversion systems efficiency improvement and, finally, fossil and fissile resources substitution by renewable energies. In addition to a more rational and efficient energy use, energy system in *itself*, from resource extraction to useful energy delivery, contains a significant potential in both energy saving and renewable energies utilization.

Nevertheless, shifting the energy paradigm and designing energy systems based on their efficiency and ability to valorize local energy resources at a territory scale lead to an increased complexity of possible technology based solutions. Main issues to be faced are related, on one hand, to resources and needs spatial disparity and, on the other hand, to non-simultaneous demand and production. This spatio-temporal resolution for energy systems induces new technical challenges that massively impacts local distribution infrastructures. Indeed, perturbations on energy systems are generated in a bottom-up way by both final consumers and numerous non-flexible decentralized production systems. These supply networks disturbances, induced by more sustainable energy productions, are and will be the cause of a large number of investments in the short term. Therefore, any expense should aim to make the system more sustainable, robust, less expensive to operate and, if possible, generate new incomes. Owners and operators of these infrastructures will have to choose what are the best technological solutions, depending on each specific territory, and comparing solutions of different types: designing a district heating network, strengthening an electric line, integrating a local thermic or electric storage, etc.

The challenge and a part of the solution is a combination of storage and multi-energy conversion systems. This combination allows energy systems to adapt to an increasingly more decentralized energy production, interacting with existing networks. These “smart solutions” for energy management and conversion increase interoperability capabilities between different energy vectors and open opportunities to develop complementary services to the one based on existing infrastructures.

1.1 Added value for local stakeholders

For energy utilities, the proposed approach will enable them to simultaneously consider a large number of solutions which are different by nature (rational use, production, distribution and storage of energy), putting them in competition and comparing, in this way, their global performances at a territory scale, as well as their economic performances. Thus, it will support their decisions to optimize their energy systems design and thereby their multiannual investment plans. Examples of such tool are given in point 3.2 and 3.3.

For city planners, access to energy data at an urban territory scale and their share with other partners will be an open door on “smart city” creation. Firstly, access to these data will enable to identify and monitor territorial energy uses at different scales (3.1 and 3.2). In this way, it is an exceptional monitoring tool of local energy and climate policies implementation. Secondly, through the collaboration between city departments (energy department, transport and mobility department) and local utilities, such a decision-making environment will allow scenarios modeling and simulation for future city energy systems in order to refine energy and climate policies programs and to arbitrate investments in different project opportunities. Finally, access to these spatialized data will support urban development, in its broad sense, in the goal of determining future urban planning according not only to collective transport criteria but also to infrastructures criteria of collective energies or energy resources availability (renewable, thermal wastes): new building zones, energy-intensive businesses implantation or companies with heat wastes (e.g. data center).

For consumers (inhabitants, SMEs or big companies), results of territorial energy system approach is of great help to take decision. As all information are spatialized, advanced users oriented tools can be developed (see 3.4) and give information and advices based on users profiles (spatial profiling). Each consumer then has access to his specific opportunities (e. g. local regulations regarding PV plants integration), to local energy strategies implementation in his land parcel, to energy resources and infrastructures available in his neighborhood (district heating, low enthalpy geothermal heat, gaz grids, etc.). Such user centered personalized communication platform enhances implementation of energy strategies.

Finally, share of data between different stakeholders could largely increase added value of each energy data. In the future, consumers will for example benefit from personal dynamic consumption data, based on smart metering from utilities, and refine the information system with personal up-to-date buildings data (refurbishment, electrical appliances characteristics, etc,). Such detailed knowledge could deliver this type of information to local utilities, or to a third actors as Energy Services Company – ESCO -, about electric or thermal load shedding potential, opening new opportunities for energy services platform development [1].

2 METHODOLOGY

Territorial energy systems approach consists in analyzing all energy aspects of a territory in an integrated and simultaneous way (needs, resources, conversion and storage technologies). It allows to systematically consider a large number of solutions, different by nature (energy vectors and technologies) and to compare them in term of global performances at a territory scale.

As mentioned in the introduction, this approach is based on data gathering and structuring. Current energy state comprehension of a territory widely depends on available data quantity and quality. First step of this approach then consists in collecting, processing and structuring energy data (see 2.1).

Then, possible evolution of the analyzed territory has to be conceived, and assessed. Simulation models and tools are the second step of this approach, allowing to calculate and benchmark energy-climate performances of different scenarios designed by engineers (see 2.2).

Using new computing and algorithms capabilities, third step consists in a numerical optimization of local energy strategies, considering current and future energy demands, as well as energy resources. This optimization phase aims to automatize scenario designs, accelerating project processes and guarantying that all opportunities are well taken into account (see 2.3).

Finally, even the best possible calculation tool is not relevant if it is not accessible to users. Forth step consists in designing and developing advanced and professional users interfaces (see 2.4)

2.1 Data collection and process

The biggest energy data collection challenge lie in identifying what are the most standard data available for a large scale territory, like a country, a state or at least a region. Indeed, models, simulation tools, or geographical information systems – GIS - need to access standardized database, with defined structures. In each case, collected energy data require preprocessing in order to validate them, estimate missing data and organize them in a format and structure enabling standard database feeding. In this sense, new preprocessing tools have to be developed for each new source database: the larger scale the source database will cover, the lower will be the number of preprocessing tool that have to be developed. This research of standardized large scale database applies for energy demands, as well as for energy resources, energy waste, and energy infrastructures.

2.1.1 Energy needs and consumption

An ideal situation, considering energy needs data, is a completely accessible smart metered territory, with high frequency measures for each consuming device. This vision is supported by the Internet of Things (IoT) R & D, but reality is still away from such an ideal.

In-the field, numerous databases exist, but they belong to different stakeholders and are protected by privacy lows. They contain low frequency energy data and often low quality data. An overview of such databases in Switzerland is given in Tab 1.

Tab 1 : Swiss energy demand related database

Database	**Short description**	**Scale**
Buildings and households register	Building : geographical coordinates; address; category; period of construction; number of level; refurbishment	Switzerland
Utilities	For each meter : Building address; energy consumption; energy bill, meter statement date (frequency from 1 month to one year)	City / region
Land cadaster	GIS data : land parcel; buildings geometry; building ground surface	City, state, national
Chimney sweep	For each boiler : building address; energy vector; power	City / region
Fire protection	For each oil tank : building address; volume	state

Once accessible databases have been identified for the analyzed territory, and relevant data have been processed in right format, first step consists in making a spatial matching of all databases, assembling all relevant information for each buildings.

Based on these reconciled data, different indicators can be defined or computed, such as energy consumption (Figure 1), heated surfaces, or energy performances for each buildings [2]. Thus, maps, as indicators of current energy demand, can be generated. Furthermore, aggregated indicators, as spatial thermal demand (e. g. MWh-heat / hectare) can be calculated (Figure 2) [3], pointing out the most interesting area for expansive energy infrastructures deployment (district heating or cooling).

Figure 1: Building thermal heat consumption, for a 40'000-inhabitant city (fake data)

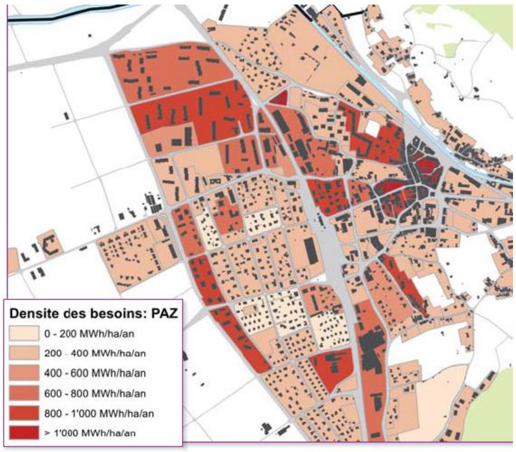


Figure 2 : Thermal demand density zone Plan [3]

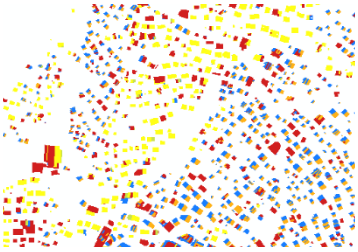
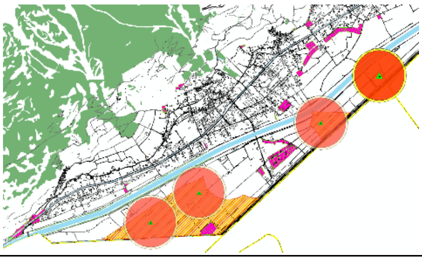
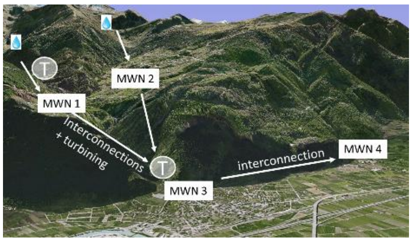
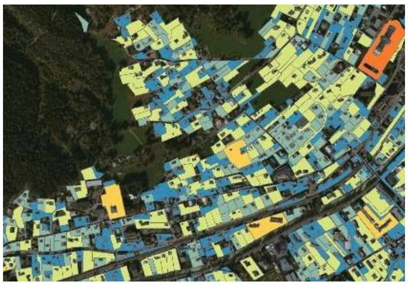
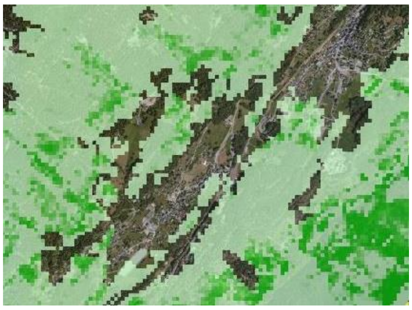
Based on city development strategies like demographic growth, zone plan, or refurbishment rate, future energy demand also has to be calculated, guarantying that investments in infrastructures will be recovered over the middle / long term.

2.1.2 Renewable energy resources

As for energy demands, goal of this second data collection and process is to generate energy resources maps, characterizing energy availability, potential, and location. Previous objective of defining methods as standardized as possible remains for each type of energy resources.

Renewable energy resources are then evaluated in a systemic way, guarantying that they will all be taken into account for each studied territory (Tab 2).

Tab 2 : Evaluation of renewable energy potential and location

Energy source	**Collect and processing**	**Maps**
Solar	Based on meteorological data, simplified 3D buildings model and regional topology, solar irradiance on each building roof surface is computed. Then, thermal or electrical (photovoltaic) potential of each roof surface is estimated.	
Wind	Based on wind data at national level, local regulation (distance to buildings and households), technical constraints (distance between two wind turbines, efficiency, etc.), possible implementation and potential production are calculated	
Hydro power	Mini hydro-power-plants, or at least feasibility studies, already exist. Resulting potential are taken into account. For existing infrastructure (like drinkable water networks), a dedicated methodology has been developed [4].	
Geothermal low enthalpy	Based on surface lithology layers, and thermal properties of rocks, a first map of thermal conductivity is realized. Then, considering constraints, as distance between drillings, local regulation and already built surface, geothermal low enthalpy potential for each land parcel is computed.	
Wood	Based on LIDAR[1] data, a scatterplot representing forest is processed to generate a Digital land surface model. Using this first result, forest statistical models, as well as forest inventory data for calibration needs, a forest energy resources cartography is realized [5].	

Other renewable resources, such as organic waste, are estimated considering statistic data (waste quantity per people and per year; rate of organic waste considering global waste quantity,

[1] Light detection and ranging technology

etc.). As they can be easily transported to a plant (incinerator, methanization), they are not spatialized at this time. Only their annual potential is used during evaluations of future territorial energy strategies.

2.1.3 Energy infrastructures

Local Energy infrastructures (gas networks, District heating or cooling networks, power grids, etc.) could be either an opportunity or a barrier, for local renewable resource or waste energy valorization.

Indeed, local authorities are often owners of these infrastructures in Switzerland, or at least have shares in companies that own these infrastructures. In this sense, companies or communities owning these networks could slow or stop a more sustainable project if it directly compete unamortized infrastructures.

Conversely, energy networks are necessary to transport and distribute renewable or waste energy, considering spatial discontinuity. Low temperature thermal networks, valorizing low enthalpy cooling or heating energy from a lake, are an emblematic example. Profitability of such an infrastructure could be largely increased, if valorizing existing infrastructures is possible.

In all case, existing energy networks have to be taken into account in this territorial energy system approach. Best practices have shown that involvement of all local energy stakeholders (DSO, utilities, etc.) in the project even accelerate its implementation in-the-field.

2.2 Simulation

The "data collection and process" step results in data sets characterizing territory energy needs and resources, spatially structured in GIS layers. Simulation then helps to understand a real world phenomena in a reduced or simplified model.

Based on this, numerous territorial energy indicators are calculable. For example:

- For a whole territory or even sub-parts of it, it is possible to define energy independence, as rate of local renewable energy valorized, compared to global consumption.
- For a whole territory, since local renewable energy potential is known, current use of this potential, as well as benchmarks between current consumptions and renewable potentials are possible.

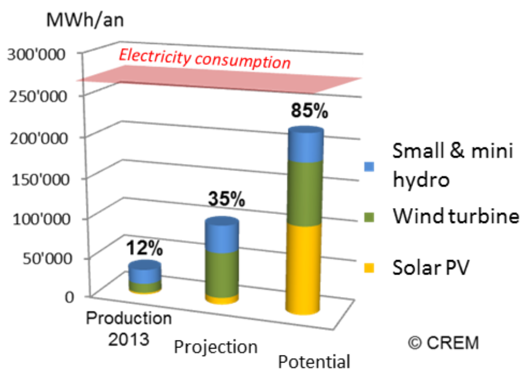


Figure 3 : Benchmark of electricity consumption, current new renewables production and potentials, region of Martigny (Switzerland)

Since territorial energy system approach aims to help local decision makers to take decision, this simulation is then used to evaluate what will be the impact of measures that could be implemented as in-the-field project. Considering knowledge and available indicators about territorial energy performances and potentials, engineers have to design territorial energy scenarios that fit local specificities (strengths and weaknesses). Simulation tools will then compute economical, energy-climate and environmental indicators, allowing to compare performances of designed scenarios. A set of typical measures are given in (Tab 3).

Tab 3 : Typical measures used in territorial energy strategies

Measures	**Description**	**Models**
Building refurbishment	Considering a refurbishment rate, as a local authority objective, possibly coupled with buildings selection rules (older than 1990, etc.), simulations estimate what will be future energy consumption for a given year (2035).	First estimation based on statistic index (kWh/m2*an) and percentage of energy saved; Complete building physic simulation
Renewables production	Considering renewables potentials (see 2.1.2), and city objectives, simulations estimate annual energy produced for each zone	Library of simplified renewable technologies models, based on spatialized resource potential and efficiency
District heating networks (DHN)	Considering spatialized thermal needs, local renewable or waste heat, and territorial heat density, simulations evaluate performances of DHN deployment, taking into account sourcing strategies (natural gas, geothermal, wood, etc.), for each selected area.	Yearly energy balance, no network operation consideration
Energy vectors substitution	Considering current thermal energy vectors for each buildings, simulation models calculate performances of energy conversion technologies substitution (e.g. from oil boiler to heat pump, or heat exchanger – DHN)	Library of conversion technologies simplified models, based on efficiency and key factors (like heat temperatures for heat pumps)

Thanks to simulation frameworks, including all models described hereunder, and to spatial data, all measures can be calculated simultaneously. For a whole territory, or a part of it, cross measures are typically:

- DHN deployment and building refurbishment
- New buildings connection to DHN, impact to sourcing strategies: all wood or waste energy is already valorized, each new consumer increases DHN natural gas supply rate
- New renewable energy injection in energy networks: power to gas, large scale solar power plant to thermal grid, etc.
- Finite resource mitigation: local wood, geothermal low enthalpy, etc.
- Space use mitigation : solar thermal or photovoltaic implementation, etc.

Results of such simulation environment is presented in point 3.1 – PlanEter Tool.

2.3 Optimization

Whenever an energy system is well understood and the question arises “What is the best possible energy system?” for a given situation, an optimization approach can find the answer. The optimization can consider a wide variety combinations. A human cannot cope with so many combinations.

In urban energy system design, the following problems need to be solved:

- Superstructure level (also called synthesis level): A superstructure is used to include in a single problem the possible options for the energy system design and to describe their possible interactions. Solving the superstructure based optimization problem therefore results in the equipment selection and in the definition of the system configuration (i.e. how the units are interconnected),
- Design level: sizing of the selected equipment,
- Operation level: mass flows, temperature levels, pressures, part load behavior and ramp up and down times leading to an operational strategy.
- The relevant topics in the field of mathematical programming are reviewed by Grossmann [6], even though he restricts himself to enterprise-wide optimization where his paper is also (or especially) valid for system engineering:
- Solving mixed integer non-linear programming (MINLP) problems remains a non-trivial tasks even though progress has been made and continues to be made in this area. Therefore a majority uses approximate mixed integer linear programming (MILP) solutions in combination with different strategies.
- Stochastic programming for the integration of uncertainty.
- Decomposition approaches use either a Lagrangean [7], Benders [8], bi-level [9] or rolling horizon approach [10].
- Multi-objective approaches are based on either transformation, non-pareto or pareto approaches where the latter two depend often on meta-heuristics (but could also use one of the decomposition approaches mentioned before).

Formulating a problem is generally easier than solving it. Grossmann [6] review already points out that solving MINLP is not trivial, using an approximate MILP instead can be solved more easily.

The optimization problem can be solved either simultaneously or in a sequential way. The sequential way is typically using an explicit or pre-defined description of the different options extracted from the superstructure, the sizing is typically done by a heuristic algorithm and the performances are calculated using simulation tools in which the operation strategy is typically defined by a set of rules. The use of an optimization technique using a black box approach is then typically used to calculate the optimal sizes of the equipment.

In the simultaneous approach, the difficulty comes from the size of the problem and its non-linear nature. A detailed review can be found in [11].

Generally, a lot of different configurations (or scenarios) are possible, when choosing the equipment for an energy system and therefore it is not possible to calculate themall by hand. Often, the 3 problems listed above are solved in a step by step approach, which is practical but does not guarantee to give optimal solutions.

Using optimization techniques in order to systematically find best solutions is an obvious answer to these problems. On the level of the synthesis, Voll [12] proposes an automated optimization framework. Compared to by hand selection of scenarios, the superstructure free approach allows studying a high number of combination by defining who can be connected to whom. Curti et al. [13], Bürer [14] and Weber [15] pre-define them.

On the design level and operational level, pinch analysis [16] with the design of heat exchanger network is a proven methodology. Pinch analysis is generally solved with MILP formulation [17] and [18] at relatively low cost in case of single period problems. The multi-period formulation [9] of the same problem multiplies the number of binary variables as a function of number of periods. This formulation is therefore computationally heavy. Marechal and Kalitventzeff [19] extended the method for the integration of energy conversion systems.

For big models, decomposition algorithms can be an elegant solution. Iyer and Grossmann [9] propose a bi-level decomposition to solve their multi-period problem. Grossmann [6] does not mention the decomposition via genetic algorithm, described in different articles [20]. Proving optimality of this approach is difficult and cannot be done. Because the genetic algorithm uses a black-box approach for solving the underlying steps, it can be slow in convergence. Rios and Sahinidis [21] compares different derivative free algorithms and shows that better algorithms exist than a genetic algorithm. If the proof of optimality is not important, Fazlollahi'smulti-objective decomposition approach [11] can be used and has successfully been demonstrated.

For the goal of thermal storage integration, pinch analysis [16] is a proven approach [22]. Pinch analysis [16] was initially developed as a steady-state model for continuous industry processes. The introduction of a "dynamic constraint", [23] where the state t-1 depends on the state t , into a steady-state model allows for linking the heat cascades of different periods over the storage model together. This so-called time slice model [16] considers variations as function of time. This enables to consider stochastically available resources such as solar energy as well as energy storage options within one model. In a simulation based approach, Angrisani et al. [24] shows that considering the temperature levels is a key point for calculating the system performance when integrating a thermal energy storage.

When comparing formulations of the same problem, Ommen et al. [25] shows that when using optimization of an energy system with storage in a dispatch problem, the linear problem (LP) can lead to similar solutions with only linear constraints in terms of cost than the MILP formulation with more constraints such as part load efficiency. However, the operating strategy changes based on the optimization approach in his model, where the heat pumps are used more in the MILP model than in the LP model. (Without knowledge of which solver settings are used for the MILP problem, there is a chance that a smaller MILP gap changes solution and might be closer to the one of the LP problem.) His MILP model solves in about a minute compared to the detailed NLP problem with about 14 hours of calculation time giving very similar results.

Even though academics provide methodologies for solving these typical problems, they are not very frequently used in industry or on a (local) energy utility level, because introducing all constraints to get to feasible solutions is either judged to be impossible or too time consuming [26]. In addition decision makers often prefer a solution that they understand compared to a solution that they don't understand but that is better according to an optimization model. Instead, engineers still rely on their experience and simple scenario analysis with very few choices to identify the best solutions. When the problem is simple enough, experienced engineers can find the optimal or a close to optimal solution.

From a practical point of view, the multi-objective analysis is often criticized, because it does not give one solution but a Pareto-frontier of solutions. Therefore a multi-objective analysis does not tell which of the proposed solution is the best one, it helps however to identify the trade-off of the different objectives for the energy system. Additional methods are applied to identify the best solution such as clustering the solutions in groups or the introducing weights for each objective. This means besides the fact that time needs to be spent on calculating the Pareto frontier, another algorithm chooses one point out of all solutions. Often industry partners have not been convinced about this approach even though they agree that conflicting objectives exist, they prefer using a single objective approach using costs. When they see a Pareto curve, they only look at the cost minimum. This implies for the results presentation that a few well-chosen points are enough. With a multi-objective optimization, the result for each objective can be that point.

2.4 User interface

Each stakeholder has its own needs and habits. Access to data, indicators and representation, strongly depends on users' needs.

- Decision makers, like politicians or urbanism services, work on a global maps basis, including zone plan, and on a long term perspective. They want to assess effects of territorial energy measures, in order to define a strategy and assist, or force, future regulations or investment decisions.
- Utilities have to implement strategies decided by their decision makers (public or internal). They need the same kind of data, but with more precision. They will have to size equipment and infrastructures, in order to operate them once they have been implemented. They need working tool allowing them to interact with data, simulate performances and maintain overall up-to-date energy data.
- Civil society, citizen or companies, have to dispose of the right information, at the right time. They do not need access to global maps, except for emulation between them, but they need access to personalized information, based on city energy strategy, local energy offers provided by utilities, subsidies, and respecting regulation. If they do not have access to this information exactly when they have to invest (building construction, energy conversion technologies turnover), and considering buildings and technologies lifetime, they potentially could take bad decisions having a long term impact.

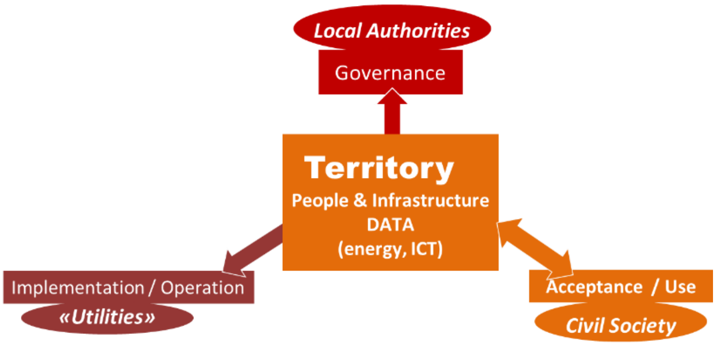


Figure 4 : territorial energy systems approach aims to develop users dedicated tools, connecting them through interoperable energy databases

Conversely, data needed to feed different users oriented tools are always very similar, as explained in point 2.1. A key point of this territorial energy system approach then consists in developing dedicated user interfaces, yet guarantying connections between different tools, especially regarding databases interoperability.

3 EXPERIENCES AND RESULTS

3.1 PlanETer

PlanETer is a help decision tool dedicated to territorial energy planning. It led to the creation of Navitas Consilium SA start-up (NCSA) that aims to valorize territorial energy systems tools and innovations generated by CREM and its partners.

Its core function allows to process mass data, spatialize and display them on maps, and calculate energy needs and productions evolution scenarios on a given territory. These capabilities place PlanETer at the cutting-edge of spatial tool design for energy planning. A key features of this tool lies in a continuous spatial anchoring from data collection and structuration to energy simulations.

An overview of this methodology is available in chapter 2.

3.1.1 City of Yverdon – case study

In 2013, Yverdon-les-Bains municipality (29'000 inhabitant) decided to conduct a territorial energy planning study in order to define an energy development strategy by 2050. This study had to be at the basis of internal strategy reflections and sectoral detailed energy studies.

Its main objective was not only to work towards a more sustainable energy supply but specially to comply to 2’000-watt society criteria in term of energy by 2050.

Geothermal resource was a key element of this mandate. Beside a scheduled large scale urban restructuration (especially between the train-station and the lake), SEY (Yverdon Energy Services) intended to exploit medium depth geothermal energy in order to cover an important part of Yverdon territory needs.

Moreover, SEY asks NCSA to closely examine thermal valorization potential from the lake water through a low temperature DHN implementation.

Figure 5: Energy zone plan

Figure 6: Zone plan thermal density

Three energy development scenarios were shaped by NCSA based on hypothesis previously discussed with local authorities. Energy systems proposed by zone are centralized and decentralized systems that deeply vary:

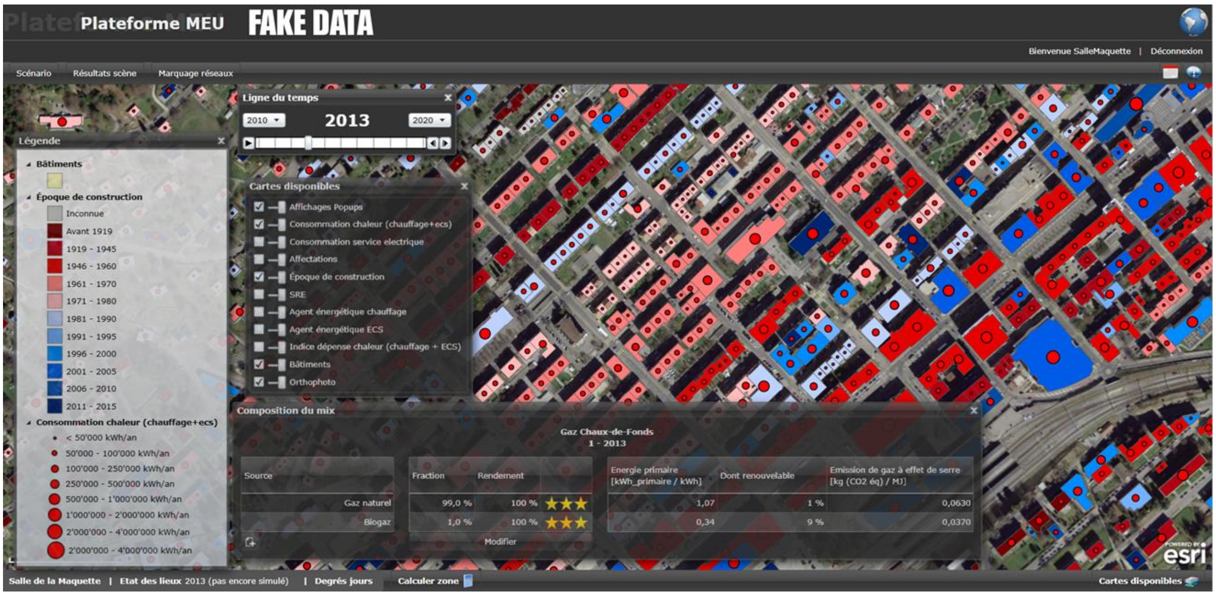
- Buildings refurbishment at different time scale with prioritization identification;
- Low and high temperature DHN from lake or Thièle river water using water/water heat pump for heating or direct for cooling;
- Medium depth geothermal energy DHN;
- Wood DHN (from a boiler or combined heat and power) with gas or solar thermal auxiliaries;

- Low and high temperature DHN supplied by a vertical geothermal probes field with heat pumps substations partly powered by solar PV farms;
- DHN using thermal waste from water coming out of the Wastewater Treatment Plant (WWTP);
- Vertical geothermal probes coupled with individual ground/water or air/water heat pumps partly powered by solar PV installations;
- Boilers or combined heat and power, partly using gas with solar thermal auxiliaries;
- Solar thermal auxiliary installations.

These study outcomes offer to SEY and local authorities a way to orient their global energy planning strategy and define potential supply solutions for current and future urban development projects.

3.2 MEU Platform

The MEU project (MEU standing for *"Management Energétique Urbain"* in French, i.e. Urban Energy Management) [28] [29] was brought forward in close cooperation between academic partners, four Swiss cities – i.e. La Chaux-de-Fonds, Lausanne, Martigny and Neuchâtel – as well as the local multi-energy utilities – i.e. Viteos SA, Sinergy SA and Services Industriels de Lausanne. The tool has been thus built following the specs agreed upon by all partners, based on their operational workflow and concrete needs in terms of energy monitoring and planning, in a real-scale bottom-up approach. The resulting MEU GIS-enabled web-platform gives access to detailed monitoring and planning functionalities for both energy demand and supply at individual building, district and complete city level (see Figure 5)



.Figure 5 : User interface of MEU platform – Buildings colors is based on construction period; red circles diameter is function of thermal consumptions; low pop-up give natural gas sourcing strategy; Yellow stars characterize data quality

The MEU platform presents the following main technical characteristics and functionalities:

- cartographic GIS-enabled interface as main working environment, with possibility to readily switch years (depending on available data);

- web-based platform fed by way of a GIS-enabled services;
- calculation of a complete set of energy-related and environmental yearly indicators for an urban zone at both building (demand) and supply levels, which can be displayed either as detailed tables or as maps and easy-to-visualize symbols;
- continuous monitoring on a yearly basis of detailed energy flows, aggregated and individual buildings consumptions, as well of the energy-related actions, by way of a temporal GIS-enabled database representing a faithful detailed energy picture of the city at any available year;
- step-by-step comprehensive approach to urban energy planning by way of scenarios directly created by the users – with typical user-friendly library functionalities -, on the basis of real data for a given year;
- detailed description of energy conversion systems and services at the building level;
- characterization of energy networks in terms of feeding supply (so-called marking), losses and GIS spatialization;
- estimation of incomplete energy consumption data at building level by proven methods;
- management of data quality and sourcing by appropriate metadata structure.

The methodology behind all the energy calculations performed by the MEU platform is extensively presented and commented in [27] [28] [29]. The platform allows considering real or estimated energy consumptions down to the single building level up to city-wide aggregated computations. As outputs, the user can also compute primary energy global balances (which can be further sub-aggregated by services or by energy vectors), share of renewable energy sources and GHG emissions.

The MEU platform is particularly suited for interactions between local authorities and energy utilities, since it allows to get a detailed well-documented of the energy-related issues on a municipal level – leveraging on the cartographic view -, as well as detailed evaluations for future planning projects. On the other hand, the existence of a reliable database comprising all the energy-related data of a given municipality for any given year, enables new kind of relationship between cities and mandated consulting companies, leading to more appropriate and focused reporting. Finally, communication with public at large and with local stakeholders involved in city projects can be made more understandable and participative upon using a GIS-enabled cartographic platform such as MEU. Experiences in this direction have been conducted in the involved partner cities with positive results.

Whereas the first version of the MEU platform allowed launching calculations for only up to several hundreds of buildings at a time, the refactored version presently gives access to entire cities comprising several thousands of buildings with the same level of detail. On one hand, the code architecture has been thoroughly revised and consolidated while, on the other hand, the databases for the four partner cities are being completed, checked, corrected and eventually made completely available for several years. In the upcoming months, the latter will present both new and improved functionalities, all the while the first version of the platform is already being used by the partner cities and utilities.

New functionalities are concomitantly being added to the MEU platform, in particular at the level of the energy networks. Indeed, in the prototype version, the latter were only displayed but no network attributes (except geo-referencing) were neither introduced nor used in calculations. The envisioned new functionalities will enable to start filling this important usability gap by adding network detailed attributes to the database structure and by allowing pre-dimensioning calculations based on selected energy scenarios and including the networks characteristics (such as available power, temperatures/pressures, limiting dimensions and others). The energy supply-side aspects will thus be quantitatively taken into account, along with the implications in terms of network extension/densification quantitavely determined. The natural gas network, which is – and shall continue to be - broadly present in all four partner cities, representing up to 30 % of the overall final territorial energy consumption, has been used as the first test case, in close collaboration with local multi-energy utilities.

One of the strategic future directions in which a tool such as the MEU platform could prove of fundamental importance towards a coherent management of energy-related data for an urban zone is the burgeoning field of smartcities [30]. Indeed, the MEU platform, as a decision-support tool designed for territorial stakeholders, could be used within a broader integrated, multi-network co-simulation platform, aimed at fostering energy networks interoperability. This approach would have high impacts not only in terms of increased energy efficiency and supply robustness, but also in terms of optimization of future network investments.

3.3 Smart Heat Design

Smart heat design describes a tool chain that focuses on the heat side of urban energy systems.

PlanETer can deliver this heat demand and supply information and is used during the project, starting from the characterization of the heat demand and of all available renewable (and local) resources in a given area. Based on the annual demand from PlanETer, a dynamic building simulation, bSol, is run to obtain hourly profiles. The data of PlanETer is enriched with typical usage profiles for each type of building. The results of the hourly simulation contain the daily as well as the seasonal variations of the heat demand. A simplified solar heat production model provides the same information for any given solar thermal panel.

Because 8760 hours contain unnecessary repetitions of data and ask for too many computational resources, the heat demand and supply are reduced to key representative days with the help of clustering. The k-medoids clustering technique choses 7 to 12 representative days within the annual hourly data sample to represent it respecting the energy and power balance.

The optimization model can then use the representative days to choose, size and operate the equipment. The optimization model relies on the heat cascade to integrate especially the heat (and cooling) into the system. Especially different type of storages can be compared: Either heat can be stored within a hot water tank over seasons or only over an individual day. Or a building's heat capacity can be used to do the same. All utilities can be integrated to function within the system, such as boilers, heat pumps or co-generation units [31].

In a final step, parameter uncertainty can be analyzed to identify key parameters. A robust optimization on the key parameters can quantify the additional costs for a system that can reply to any kind of perturbation.

3.4 PlanETer online

Last but not least, even with an ambitious and detailed territorial energy strategy decided by local authority, the energy transition will be implemented in-the-field only if final consumers (citizen and companies) engage themselves in this way. PlanEter Online platform has been created to answer this need, giving them free access to all relevant public energy maps and information.

Based on ArcGIS Online technology, PlanEter online publishes on the Web all maps and data from PlanEter (see 3.1). For a local authority, the goal of this information tool is to communicate its energy strategy, aiming to sensitize and help decisions of all local stakeholders (citizen, companies, communities, engineer offices, utilities, etc.). The biggest added-value of this tool is embedded in spatial profiling capabilities: for each stakeholders, a click on a selected building / land parcel gives access to a set of personalized information.

Moreover, a secured access for city administration, gives access to all confidential data from PlanETer that belong to the local authority. Same spatial profiling functionalities allow city managers to access to specific information for each building / land parcel.

3.4.1 User functions

Main user interface consists in an interactive map, where users can access, by clicking on land parcels, to different information about renewable energy resources, existing energy infrastructures, and local authorities recommendations (see Figure 6).

Figure 6 : Online map of solar photovoltaic cadaster and DHN deployment areas; Pop-up windows give specific building and land parcel information concerning solar energy potential and recommended heating technologies

Information available through maps and personalized pop-up are [3]:

Tab 4 : Pop-up public and secured information by clicking on a land parcel / building from PlanETer online

User functions – pop-up	Access
Parcel ID number	Public
Buildings heated surface [m2]	Secured
Reference year (construction or refurbishment)	Secured
Heating and warm water energy vectors	Secured
Thermal consumption [MWh/year]	Secured
Installed thermal power [kW]	Secured
Thermal energy vectors recommended by local authority	Public
Interdiction (e.g. drilling for heat pumps)	Public
Solar thermal and photovoltaic potentials [kWh/(m2*year)]	Public

Tab 5 : Public and secured maps layers from PlanETer online

User functions – Maps layers	Access
Geographical boundaries (city, community, etc.)	Public
Land parcels	Public
Public buildings	Secured
Heating & warm water energy vectors per building (building perimeter color)	Secured
Building typology and reference year (household, hospital, school ...)	Secured
Reference years (map color code)	Secured
Heated surface per building (map color code)	Secured
Buildings consumptions (variable size circles, concentric with building)	Secured
Hectometers thermal needs density (map color code)	Secured
Solar thermal and photovoltaic cadaster	Public
City energy strategy (energy zone plan, considering infrastructures availability)	Public
Geothermal drilling regulation	Public
Water protection areas	Public

For the purpose of informing and involving all local stakeholders, and not only specialist, technical sheets have been created and explain how to operate different proposed technologies, such as DHN, heat pumps, wood boiler, solar thermal or photovoltaic, building refurbishment, etc.

Likewise, financial sheets have been published, presenting all subsidies or regulations available at every governance level (national, state, city) [32]. They not only explain what kind of support (financial or technical) is available, but also give access to procedures in order to benefit from this support or subsidies. In some cases, direct links to official forms are directly given.

An address search function has been integrated in this tool to facilitate users' navigation in the case they would not be familiar with GIS Web interface.

Finally, centralization of all data in a single advanced Web Platform allows all stakeholders to quickly access to relevant information considering energy transition, from technical to financial or regulatory aspects, and based on spatial profiling. As a result, PlanEter Online is a powerful tool that helps local actors to move from commitment to action, helping local authorities to implement energy strategies.

4 CONCLUSION: EMERGENCE OF TERRITORIAL ENERGY SYSTEM APPROACH

Policy, evolving market dynamics, new technologies and social pressures are strongly impacting energy systems. Main issues at local scale, are:

- More energy efficiency, decreasing GHG emissions, and possibly energy infrastructures profitability.
- More local and decentralized energy productions, valorizing renewable resources such as solar, mini-hydro, wind, geothermal, as well as recovering waste energy. These local production will be self-consumed by producers, or injected directly in distribution infrastructures
- More pressure on local energy networks, evolving from distribution infrastructure to smart infrastructure, collecting, distributing and even storing energy.
- More consumers expectations, wishing to become "part of the game". Transparency, lower prices, energy services, green offers, become producers, are emblematic needs of new prosumers.

These issues will drastically change local energy systems, forcing them to adapt to territorial specificities. A part of the solution is the combination of storage and multi-energy conversion systems. This combination allows energy systems to adapt to an increasingly more decentralized energy production, interacting with existing networks. These "smart solutions" for energy management and conversion increase interoperability capabilities between different energy vectors and open opportunities to develop complementary services to the one based on existing infrastructures.

As the problem becomes more and more complex, usual approaches considering optimization of buildings, power grids and other energy networks in a segmented way, are no more efficient, not considering integrated solutions.

Territorial energy systems approach, is then a key answer to tackle such kind of complexity. It consists in studying, simultaneously and in an integrated manner all energy aspects: energy demands, resources, and technologies. It is based on:

- Smart Cities, to better collect, process, store and share territorial energy data;
- Simulation tools, to better understand real world phenomena and plan future of energy system;
- Optimization methods, to compute best territorial energy scenarios, taking into account as many solutions as possible, and benchmarking them based on different relevant indicators (primary energy consumption, CO_2 emission, share of renewable energy).
- User interface, to facilitate stakeholders engagement and action, for local authorities, utilities, clean tech installers and producers, as well as end consumers.

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