ABSTRACT

As a consequence of the energy transition, energy systems are moving toward more distributed architectures. This paper proposes a method to co-design today’s and tomorrow’s energy systems, relying on an innovative model-based engineering methodology taking account of the requirements of all stakeholders and of the spatiotemporal and physical constraints of the system. It enables the use of simulation to verify design and operational solutions against system requirements. Thus, not only solutions but also requirements need to be modelled in languages with well-defined syntax and semantics. Requirements and high-level solutions (e.g., systems architectures) may be modelled in the innovative language FORM-L (FOrmal Requirements Modeling Language), whereas detailed solutions may be modelled using behavioral languages in place such as Modelica or Anylogic. A demonstrator called PowerGrid illustrates the overall methodology on a rather complete district energy system, embedding energy production facilities, energy consumers and appropriate networks.

Keywords: systems engineering, requirements engineering, modelling, energy districts.

1 INTRODUCTION

Today’s energy landscape faces a deep transition due (but not limited) to growing societal awareness on environment footprint, rethinking of the energy mix with a higher share of renewables, market deregulation with new actors and new subsidy mechanisms, technology progress (IoT, batteries, etc.) enabling new uses and services such as the smart charging of electric vehicles, etc. At the same time, uncertainties are growing on key elements such as the evolution of electricity prices, future European energy and climate policies, etc. No precise scenario is emerging, and while current energy systems are moving toward more distributed architectures, historical energy companies face more risky investments and decreasing revenue from energy sale. They are therefore seeking new business opportunities and establishing new partnerships at a more decentralized level.

The work presented here proposes a new method to co-design today’s and tomorrow’s energy systems, from producers to consumers through energy networks (electricity, heat, etc.) and telecommunications. The main innovation relies on the consideration of both the requirements of all stakeholders and of the spatiotemporal and physical constraints of the system. The expected benefits are:
1. Better coordination of stakeholders and hence the avoidance of over-specifications often due to misunderstanding between parties;  
2. Avoidance of oversizing: requirements are formalized enough to be confronted in simulation with models of systems behavior to assess the adequacy of a contemplated design solution;  
3. Automation of the validation phase and hence a more robust engineering approach where changes in requirements or design are thoroughly assessed, and all contemplated scenarios are systematically tested.

The rest of the paper is structured as follows: Section 2 provides a brief overview of the proposed approach; Section 3 presents the PowerGrid demonstrator; Section 4 shows how the proposed approach has been applied to the first engineering step of the PowerGrid demonstrator; finally, Section 5 provides a few words of conclusion. Unfortunately, due to paper length limits, the FORM-L language cannot be described in any detail but related works are given in the references section.

2 OVERVIEW OF THE NEW REQUIREMENT-BASED ENGINEERING METHODOLOGY

A key objective of the suggested methodology is to use simulation to verify design and operational solutions against system requirements. Thus, not only solutions but also requirements need to be modelled in languages with unambiguous syntax and semantics. Detailed solutions may be modelled using behavioral languages such as Modelica or Anylogic. Requirements and high-level solutions (e.g., systems architectures) need to be modelled using constraints-based languages. In a typical setup, a model (hereafter called a reference model) specifies the system requirements from the concerned stakeholders, and one or more models describe the various aspects of a solution. These models are then simulated together, and for each simulation case, the behavior displayed by the solution models is automatically checked against the reference model.

Another key objective is to support the engineering of complex systems, where multiple stakeholders and multiple design teams (working on different parts of the system or representing different disciplines) need to cooperate, and where detailed solutions are discovered progressively, after multiple engineering steps.

Extensive surveys of constraints-based modelling languages showed that although there are many languages for purely cyber systems, none existed that satisfied the needs of complex cyber-physical systems (Azzouzi et al. 2019). Thus, language FORM-L (FOrmal Requirements Modeling Language) was developed within the ITEA 2 project MODRIO, together with the principles of the methodology presented here (Bouskela et al. 2017, Nguyen 2017).

2.1 Step 1: Setting a Reference Model

An important condition is that the specified requirements represent what is really expected of the system. Meeting this most essential condition is not always obvious: often, errors are not (or not only) in the solution, but (also) in the requirements specification. The approach to reduce the likelihood of inadequate requirements is in a large part based on the notion of reference model defined as below:

- It is a FORM-L model, i.e., requirements are specified in a formal hence unambiguous manner.
- It considers the system of interest as a black box.
- It includes the environment entities interacting with the system or placing requirements on it. They may be technical, human or physical (e.g., the atmosphere).
- It lists the situations the system may face: a) normal and abnormal system states; b) normal and abnormal environment states; c) operational goals assigned to the system at any instant. There are stable conditions (lasting a certain time) and transitions between stable conditions.
- It identifies flows (e.g., physical fluids, monetary quantities, information or events) between the system and its environment, depending on situations.
- It models the assumptions made on the environment, which may also depend on situations.
- It models the top-level system requirements, which may also depend on situations.
A reference model needs to be verified and validated. Classical techniques such as inspections (where models are read and analyzed by competent but independent persons) and reviews (where the modelling process and the related documents are assessed also by competent and independent persons) may and should be applied (SEBoK 2018). The innovation with FORM-L relies on the fact that simulation may also be applied to check that the model behaves as expected and represents what was intended.

2.2 Step 2: Developing and Refining Solution Models

The next step is to develop a first, high-level solution that may still view the system as a black box and specify additional requirements, generally of a more technical nature. For example, the reference model may represent the system owner’s requirements and is published in a call for tender. Each bidder answers with the black box specification of their solution. Alternatively, the solution may open the box and identify the main sub-systems: it then specifies the requirements applicable to each sub-system. The solution model is then simulated together with the reference model that is used to verify that the solution complies with the essential requirements.

After this first-level solution is verified, a second design step may be made to refine and complement the first-level solution: again, simulation may be used to verify that this second-level solution complies with the requirements specified in the reference model and in the first-level solution and so on (Figure 1).

2.3 Formalizing Requirements with the FORM-L Language

Contrary to modelling languages such as Modelica which, given initial and boundary conditions determine a single trajectory, FORM-L models envelopes of time-dependent phenomena (Figure 2) rather than single, deterministic solutions, and is not limited to physics but can also address other aspects such as cost in operation or human workload, which gives more space to innovations in the design of solutions.

In FORM-L, a requirement is expressed as a formal property answering to four main questions:

- WHAT constraints are to be satisfied? This may be Boolean conditions, constraints on the number of occurrences of an event, or constraints on how long a Boolean condition is satisfied.
WHEN constraints are to be satisfied? Time locators allow a precise specification of the time periods or instants where a constraint is to be satisfied.

WHERE in the system constraints are to be satisfied? Spatial locators use sets (e.g. to specify which components are concerned) and quantifiers (universal or existential).

HOW WELL constraints are to be satisfied? FORM-L makes a distinction between desirable properties and genuine requirements. A requirement generally specifies the satisfaction of a desirable property under given fault-tolerance conditions or puts a limit on the probability of violating the property.

2.4 Related Works
During the development of the methodology, in the framework of ITEA2 projects EuroSysLib and MODRIO, a survey was carried out in order to identify existing simulable constraints-based modelling languages suitable for the engineering of complex cyber-physical systems. Although a number of them could support the engineering of digital embedded systems (OCL, AADL, etc.), almost none of them were able to meet the needs of physical systems, especially to treat temporal constraints. LTL embeds this feature but its syntax is far too unclear to most operation engineers for being used widely. This was later confirmed by a survey made by (Azzouzi et al. 2019).

In addition, the systematic use of simulation is one important difference with other requirements engineering approaches, such as the one presented by (Furfaro et al. 2016) and those based on languages that are not fully simulable such as SysML.

3 ILLUSTRATIVE CASE-STUDY: RENOVATION OF THE ENERGY SYSTEM OF AN URBAN DISTRICT

3.1 The PowerGrid Demonstrator
A demonstrator called PowerGrid is presented here as an example to develop and test the new co-design methodology on a rather complete energy system, embedding energy production facilities, energy consumers and appropriate networks. This case study is proprietary and used data from the Efficacity institute which are not publicly available. It concerns the multi-energy district of Vélizy in Southern Paris suburbs. This district, called Inovel Parc, includes:

- 720 buildings (residential + tertiary), possibly capable of practicing some self-consumption (with PV rooftops, heat pumps, etc.) and volunteering cut-offs;
- Local production and back-up units (combined heat and power plant, gas boilers, etc.);
- Heat and electricity networks with some connections to the national electrical grid;
- Telecommunication infrastructure;
- Possibly some storage devices (thermal, batteries) and electric vehicle charging stations (not modeled in the next chapter).

The goal is to examine the district in a global way and to investigate how it can be efficiently renovated to move into a more distributed architecture with a higher share of renewables and smarter services on each of its parts.

3.2 Development Process
The engineering of complex energy systems should consider some essential particularities:

1. Energy systems have a very long lifetime (several decades for power plants, etc.);
2. They involve numerous stakeholders (consumers, producers, grid operators, suppliers, etc.) whose role and number may evolve over time, and with diverse, even contradictory objectives;
3. They imply multiple subsystems (power plants, network infrastructures, buildings, etc.) interacting together among different layers and energy vectors tightly bound by harsh constraints (the electricity grid must constantly balance demand and production) and hence producing a non-linear behavior;
4. They are subject to multiple external factors (climate, energy policies, market fluctuations, etc.);
5. They are ruled by stringent societal, environmental, safety and security standards and needs.

Consequently, the new co-design methodology should be:

- Applicable all along the system lifecycle;
- Versatile enough to easily integrate any change in the stakeholder requirements or in the design;
- Model-based to assess the relevance of each design alternative for all system’s facets (physical, logical, economical, human, etc.) and to automate the investigation of extensive lists of scenarios;
- Rigorous and deductive to correctly justify any step of the design choices to the legal authorities.

To test all these features, the methodology has been applied on the renovation of the PowerGrid district thorough its three project phases:

- **Phase 0: Urban Energy Planning** which aims at defining the future architecture of the district to meet high-level requirements (such as “having a greener and smarter district”) and macro-constraints (initial investment cost and duration of the payback period, type of resources available locally for the renewal of the energy mix, etc.);
- **Phase 1: Sizing** where each part of the district (buildings, networks, power plants, etc.) is correctly designed to choose the most possible efficient compromise between refined requirements (such as “compliance with the grid code”, “building certification”, etc.) and realistic operational constraints (stability of the electricity network, intermittent nature of some renewables, etc.);
- **Phase 2: Operation** where new local energy management systems are introduced to better control in real-time some of the network flexibilities (introduction of new storage devices, volunteering cut-offs, etc.) or to maximize system performance (adaptation of the CHP production plan following market fluctuations, etc.).

This paper only addresses the urban energy planning phase. The two other phases are ongoing.

### 4 APPLICATION

#### 4.1 System’s Stakeholders

The reference model states the expectations and requirements of the PowerGrid sponsors (i.e., the bodies who decided to create PowerGrid and who push for its existence). In this first phase, only one sponsor is considered: the town council, i.e., the political body that provided the initial impulse. In later phases, other sponsors such as real estate developers might be considered.

#### 4.2 Capture of the Main Council’s Requirements with Objective KPIs

As for Nottingham city in the UK or Ungersheim village in France, one of PowerGrid’s ambitions is to provide a highly autonomous local and multi-energy (electricity and heat) system. The town council has the following expectations, considered as key performance indicators (KPI):

- **kpi1** (ratio of renewables): In any given year, the energy provided to the clients of neighborPower (the local heat and electricity supplier associated with PowerGrid) should have at least 30% of renewables (taking account of auto-consumption and imports from the national grid, Figure 3).
- **kpi2** (CO₂ emissions): Over a year, the CO₂ emissions to produce the energy consumed by neighborPower’s clients should be less than 60 g per kWh (accounting also for electricity from the national grid).
- **kpi3** (competitiveness): For at least 90% of consumers, the yearly bill with neighborPower’s best offer should be lower than the bill with competition’s best offer.
- **kpi4** (self-sufficiency): Over a year, at least 60% of the energy managed by neighborPower or auto-consumed by its clients should be produced locally.

```plaintext
requirement kpi1 when endYear
  ensure renewableEnergy >= totalEnergy*0.3;

// Renewable energy produced in a year by clients, nP and from natGrid import
renewableEnergy is yearlyIntegral(
  sum(for all c in clients: c.autoPower) + // Clients pv auto-consumption
  nP.renewableElec + // Renewable local electricity
  nP.renewableHeat + // Renewable heat
  nP.ngPower * natGrid.renewablesRatio); // Renewable imported electricity

// Total energy used in a year by clients, nP and natGrid imports
totalEnergy is renewableEnergy + yearlyIntegral(
  nP.nonRenewableElec +
  nP.nonRenewableHeat +
  nP.ngPower *(1-natGrid.renewablesRatio));
```

Figure 3: Modelling of kpi1 in FORM-L, where np stands for neigborPower and natGrid for national grid.

The terms used to define renewableEnergy and totalEnergy are to be provided by solution models.

### 4.3 Model Description

To support decision-making in an urban energy context, EIFER has developed an Anylogic toolbox based on its in-house energy systems library called EnergyLogic, which facilitates the development of models that can help to assess different energy concepts. It is based on a bottom-up agent-based modelling method, in which complex systems are represented by the interaction of the different components, in this case energy generation and consuming technologies of various kinds. Anylogic was chosen for the energy planning of PowerGrid as rapid prototyping environment to create a systemic solution model including all the relevant components of the system needed to tackle a preliminary design. More physically detailed modelling approaches such as Modelica will be introduced to support the sizing and operation steps. Moreover, EnergyLogic has already been successfully used in different urban energy planning studies, such as reported in (Oldenburg 2015), (Ge 2016) and (Bahu 2017).

Both the technical specifications of the EnergyLogic modules and the KPI modules have been aligned together with the FORM-L specifications of the PowerGrid demonstrator, allowing for a coherence between the granularity of the (EnergyLogic) solution model and the one imposes by the (FORM-L) reference model.

A particularity of the approach is that even in the early urban energy planning phase, not only aggregated consumptions are taken into account, but a building-sharp resolution is chosen that allow to select different energy measures directly building per building (720 buildings from a typology of 28 different building types). This is based on a GIS (Geographic Information System) system integrated in the Anylogic framework. Such a bottom-up model offers certain advantages that allow us to take into account spatial constraints and use space as a logical linking layer by connecting e.g. elements by spatial proximity.

The solution model to be setup is based on the case study selected for the PowerGrid demonstrator (section 3.1). The proposed energy system consists of:

- An electrical grid to supply all specific electricity and other electrical uses;
- Photovoltaic (PV) rooftop panels on selected buildings feeding locally at building level into the electricity system (self-consumption according to each building’s electricity demand);
• A district heating network (DHN) supplying heat and domestic hot water to the connected buildings;
• A Combined-Heat-and-Power (CHP) unit which cogenerates heat for the DHN and feeds in electricity at substation level;
• Several Gas Boilers (GB) that provide additional heat to the DHN;
• An electrical substation which symbolically aggregates all the real substations of the zone to simulate upper level grid interaction with the transmission system;
• Individual building biogas and gas heating systems;
• Individual geo-localized building models connected to a demand generation model. The buildings are connected to different grids depending on their heating system: some of them are connected only to the electricity grid (those having a local heating system such as biomass or a gas building heating, which again would be connected to a gas grid not modelled here), and some of them connected to both electricity and heating grid (for domestic hot water and space heating). The different connections of the buildings within their spatial layout determine the interactions of heat demand, energy networks and ultimately generation means. The representation of the system in the solution model as such allows to better analyze, already in an early urban planning phase, the interactions between the different energy vectors and their impact on the KPIs.

4.3.1 Demand Calculation

The energy needs at building level are calculated as follows:

• The heating demand is simulated in EnergyLogic using representative demand profiles at block of building levels, based on a sigmoid energy signature data-driven model described in (Koch 2016).
• The Domestic Hot Water (DHW) demand is obtained from unitary profiles provided by EDF R&D per type of building;
• The specific electricity use is obtained from profiles provided by EDF R&D per type of building;
• Cooling needs have not been considered so far.

Different types of heating systems are considered: district heating network, building gas boiler heating, electrical heating and biomass heating.

4.3.2 Central Heat Supply

For all buildings connected to the district heating network, heat is supplied by:

• One natural gas-fired heat-driven CHP plant (gas turbine), 20 MW nominal thermal capacity;
• Four gas-fired back-up boilers, providing heat during peak periods; capacity defined by thermal peak demand minus thermal capacity of CHP (here: 4 x 20 MW(thermal)). A backup system (in case of a breakdown of the CHP unit) was not considered in this setup.

4.3.3 Electricity Supply

A Merit Order for locally-produced electricity has been used: priority is given to consumption of PV production (only available on a predefined number of buildings), then to consumption of electricity from the CHP plant (for all buildings in the zone). Residual electricity demand (for all buildings in the zone) is purchased at the wholesale electricity market and sold to the neighborPower clients at a predefined retail selling price (excluding taxes and levies). All electricity sold to the grid (independently of which technology has generated it) is sold at market price.
4.3.4 KPI Assessment Used

The economic assessment considers:

- Fixed and variable investment (capital expenditures, CAPEX) and operation-related costs (operational expenditures, OPEX; including fuel costs) of the technologies deployed;
- Revenues from selling electricity and heat generated by the technologies deployed to the neighborPower customers;
- Potential costs for buying residual electricity from the wholesale electricity market (in case the demand by neighborPower customers exceeds the local production).

The following economic indicators are calculated:

- Levelized Costs of Electricity/Heat (LCOE/LCOH), i.e. the total discounted cash flow for a given generation technology (including CAPEX, OPEX and accounting for potential revenues from selling the by-product (heat/electricity) in the case of a CHP plant), divided by the total discounted amount of electricity/heat generated by this technology;
- Net present value (NPV), i.e. the difference between total discounted benefits (revenues) and total discounted costs (CAPEX, OPEX) of a technology (or set of technologies) over the project’s lifetime. A positive NPV means that the scenario can be considered profitable.

For the sake of conciseness, only two scenarios among the four scenarios modeled are selected here for a detailed analysis (Figure 4):

1. “No measures”: 0% PV on selected buildings, 0% Renovation of residential buildings (the current situation with no effort made for more renewables or a better building efficiency);
2. “High efficiency”: 100% PV on selected buildings, 75% Renovation of residential buildings (a will of being “greener” with an incentive policy and some efforts in terms of investments).

Figure 4: Selected scenarios for detailed analysis.

4.4 Simulation Results and Consequences on the KPIs

For evaluating the simulation model, a GUI was created that facilitates the interpretation and analysis of results. This allows to perform the rapid prototyping approach, in which simulations can be run frequently during model development, allowing to directly assess results while the model is improved and adapted, and in iterative discussion with the stakeholders.
In the first detailed scenario (Figure 5), no PV and no renovation is taken into account. We observe the following points on the detailed KPIs:

- A lower RES (Renewable Energy Sources) share compared to the one’s of the national electricity grid (11.2% vs 20% grid) due to CHP;
- A total self-consumption of the locally produced energy, which means that no CHP power is ever exported to the grid;
- 81% of the electricity demand is covered by grid imports;
- The system shows a NPV of ~112 M€ after 15 years due to the revenues of CHP and GB heat selling as well as electricity retailing. Retailing has a major influence on NPV.

![KPI Panel](image)

Figure 5: KPIs for the detailed scenario 1 (“No measures”).

In the detailed scenario 2 (Figure 6), 100% of the selected buildings PV have been covered at 60% of their footprint surface with PV panels, and 75% of demand reduction through renovation measures on old residential is taken into account. We can observe the following points on the detailed KPIs:

- Higher RES share (21.5%) than national electricity grid due to demand reduction and high PV;
- The heat production on the DHN is reduced from 222 to 139 GWh due to renovation measures, with a lower operation of especially peak GB and also CHP;
- Yet only very few exports of PV electricity into the grid at high production peaks (very small amount only, 1%);
- 76% of demand is covered by grid imports, which means a lower SSR than in the previous case, mainly due to higher grid imports, the heat driven CHP is producing less local electricity;

The system shows a NPV of ~57 M€ after 15 years due to negative effects of PV and a largely reduced income from heat retail (renovation investments are not yet considered which would reduce the NPV even more).
4.5 Discussion Regarding the KPIs

- Generally, the aim of the economic indicators is to give a first indication of the competitiveness of the neighborPower offer, not to describe a specific and detailed business model.
- The CHP and gas boilers are shown to be highly profitable, a result that is substantially influenced by the assumed gas wholesale market price (relatively low given market conditions in 2017 and the high amount of gas purchased). It is important to stress that energy market prices are volatile and that any projection 15 years into the future is therefore subject to uncertainty.
- The use of a gas-fired CHP and gas-fired back-up boilers, whilst advantageous from an economic perspective and for the self-sufficiency indicator, drives up the overall system's CO2 emissions, as compared to purely electrical solutions in the French context; a biomass-driven CHP would be a possible improvement concerning CO2 emissions, but has not been studied here.
- Rooftop PV is currently the main lever for increasing the share of (electric) renewable energy in the system (given that the share of RE in the national electricity grid mix is largely out of control of the neighborPower operator). However, rooftop PV comes at a relatively high cost (which is slightly reduced when accounting for the full equipment lifetime of PV). The (electrical) renewable energy share would increase with reductions in electricity demand, which is however currently not considered in the model.
- The selected zone and configuration of the neighborPower demonstrator are quite specific and not generally representative of other zones in France. The fact that renovation measures almost only affect residential buildings on the DHN affects largely the KPIs of the system, especially competitively. Furthermore, PV has been selected only on some buildings with an average share of the area covered. Therefore, result extrapolation is only valid if we consider a very similar context.
5 CONCLUSIONS AND UPCOMING WORK

5.1 Preliminary Results

This paper reflects the work done on the PowerGrid demonstrator with the new co-design methodology, that joins requirements engineering and behavioral modeling. This work consisted in:

- the definition of the reference model, that integrates the top-level requirements expressed by the PowerGrid sponsor (here the local council),
- the development of a first version of the PowerGrid demonstrator, designed for the Urban energy planning phase (macroscopic but systemic model integrating all the relevant energy components of the entire district, here modelled with the in-house tool EnergyLogic), and
- the simulation results on a first architecture of the district (close to the current one) to evaluate the impact of some renovation actions (e.g. building refurbishment or addition of PV rooftops).

In that sense, the Urban planning demonstrator has shown to be a good decision-making tool to assess the relevance and cost of the district renovation and to convince new sponsors to fund the realization phase. Further, the use of a systemic simulation approach, which was improved in an iterative way by close discussions with the stakeholders, and applying a formalized requirement (FORM-L) method, allowed to get a quick understanding of the main elements of a complex urban system, among the different stakeholders. This is a fundament and pre-requisite for further phases such as sizing and dimensioning. The granularity of the systemic simulation model used in this phase was however not sufficient to focus on the technical design of the district components (energy production and distribution facilities) which requires dedicated expert and tools. Detailed behavioral models, e.g. using the Modelica language, are indeed needed to consider e.g.:

- Heterogeneity of energy demand profiles with a statistical distribution of building’s occupancy;
- Individual building’s capacity for self-consumption depending on solar irradiation and rooftop geometry;
- Energy production and storage limitations (min. load, min. starting/stopping times…), etc.

5.2 Outlook

The Sizing Phase requires additional work on requirements modeling as well as physical modeling. Other stakeholders need to be implied: final energy consumers, network operators, owners of local energy production units, etc. Additional requirements of each of these incomers will be captured according to the FORM-L methodology in the form of contracts to make explicit the role game between the multiple stakeholders and the various decision criteria that will be used to converge to acceptable design tradeoffs.

Concerning physical behavior modeling, the planned work includes the adaptation and connection of different models built for instance with Modelica in order to get a detailed and multi-faceted model of the entire district. This resulting model will be used to simulate refined behaviors of the district so as to successfully size and optimize each district element. The detailed description of the contracts between the stakeholders will in particular drive the development of model interfaces between the sub-system models, since the fluxes stated in the contracts will be the variables to be exchanged through these model interfaces (for instance electrical voltage and intensity between the electrical grid and the buildings).

Then, once the Sizing Phase is finished, the other step will consist in preparing the Operation Phase by adapting the models to support the multi-mode and reconfiguration aspects. The main motivation is the will to test more disruptive district architectures to take advantage of operational flexibilities on the grid (e.g., volunteering cut-offs, insertion of storage devices) and possibly of smart charging stations for electrical vehicles.
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