AN ADAPTABLE SYSTEM ARCHITECTURE FOR MODULAR, STANDARDIZED AND SCALABLE URBAN ENERGY SYSTEMS

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ABSTRACT

Due to the complexity and growing uncertainty of future prices, demands and regulatory aspects of energy systems, the investment planning problem receives growing attention from municipal utilities, generation companies, contractors, and associated stakeholders. Sophisticated optimization tools optimize generation and conversion assets over multiple stages, but in practice, transactions costs and planning overhead are just too high to apply the so found solutions in a cost efficient way. Hence, a conceptual system architecture based on the three pillars of standardization, scalability, and modularity is envisioned and presented in this paper. Over time, such an architectural platform enables the small and large scale rollout of new and more efficient conversion and storage technologies, which is important to keep today's energy supply systems adaptable to (unforeseen) future necessities. Thus, this conceptual proposal is intended to initiate a paradigm change for the investment planning problem, with high strategical impact for many stakeholders

INTRODUCTION

To reduce carbon emissions on the supply side, the planning, optimization, and implementation of micro grids and/or multi-energy systems have become an attractive strategy in the last decades. However, spatial scales for this planning process, that have been analyzed in literature, vary widely between smaller (as on the building level) and larger systems (as for country-wide optimization of optimal generation portfolios). Therefore, independently of the chosen spatial scale, an implementation is often found to be not yet cost-efficient, which means most planning efforts rarely reach the implementation stage.

On the other hand, the most robust solutions are chosen often, which might still be suboptimal for the actual realization of parameters. Looking at investors, the multitude of uncertainties leads to reserved or conservative investment decisions which do not make full use of the technologies available to date. This is equally true for big generation companies (GenCos) and municipal utilities. Besides, the problem does not only exist for electric power systems but can as well be found for district heating systems. For instance, although a combination of CHP units and electric heat pumps could be used to provide peak loads and (positive and negative) operating reserve efficiently, quite often only the base heat load is covered by CHP units because this is guaranteed to be an economical operating point. Or to use the terminology of optimization, this solution is found to be more robust to parameter changes like changes in natural gas or electricity prices, or even carbon tax.

Thus, to find a solution to this problem is challenging, and literature lacks management tools to handle uncertainty systematically. The two most promising techniques that have been suggested are 1) optimal multi-stage investment under uncertainty and 2) real options management. However, they are rarely found in practice, and one of the reasons is that planning and engineering of technical solutions are as complex as introducing extra stages of investment is normally not feasible. Besides, customers want to see their projects realized as soon as possible. Telling them to rather defer an investment is often no option.

To this end, an easily adoptable system platform might be a desirable solution, where instead of investing once, an initial (optimal) solution could then be improved successively, i.e., by consecutive transitions.

To sum it up, a solution to the investment planning problem is sought-after, i.e., a concept is needed that allows an easy and cheap reconfiguration of the conversion and storage units (in contrast to the network infrastructure) to follow future political and societal necessities.

Contributions of this paper

In this work, we mainly address municipal heat suppliers, generation companies, contractors, and policymakers, and propose a technical architecture that is tailored for three things:

- It allows for a successive implementation of efficient conversion and storage solutions,
- it guarantees optimality over a long time horizon, and
- It is able to accommodate arbitrary technologies due to the modular concept.

The paper thus shows a useful starting point for the actual implementation which is at the same time harmonized with challenging spatial requirements in densely populated urban areas. Therefore, with this concept, city councils (and technicians) can find a convenient and economically bearable strategy for a local energy transition.

This paper is structured as follows: First, the investment planning problem and multi-stage investment are briefly recapitulated. Typical uncertainties in the strategical design of energy systems are then discussed to underline the necessity for a paradigm shift in planning and design of such systems. Finally, the system architecture is presented and supported by a thorough discussion and final conclusions.

UNCERTAINTIES AFFECTING THE PLANNING OF ENERGY SYSTEMS

First of all, the investment planning problem can be optimally solved, and even the optimal order and magnitude of investments has been found in numerous studies. Both concepts shall be briefly capitulated. Afterwards, to connect to typical challenges in the context of investments, some typical uncertainties shall be named here from the view of municipal utilities to prove the need for a more strategical solution to multi-stage planning.

(Multi-stage) investment planning problem

The investment planning problem is well known for different energy carriers like electricity and heat, and has been tackled by multiple approaches. Instead of recapitulating all optimization studies here, the interested reader is referred to the two reviews [1,2].
In the investment planning problem, the most economical conversion and storage units have to be determined from a set of available ones. In Figure 1 below, the candidates for integration are termed {A, B, …, Z}, and they symbolize all thinkable conversion units that could possibly contribute to supply the given electricity and heat demand. All such units come at a certain investment cost, which makes up the optimization problem.

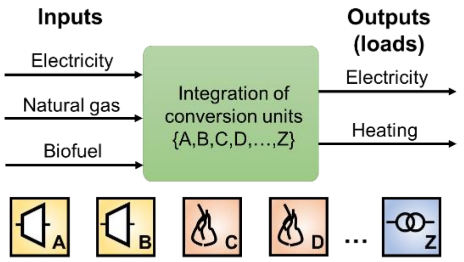

Figure 1: Visualization of the investment planning problem for provision of electricity and heat (adapted from [3])

In this example, {A, B} are two different combined heat and power units from two different vendors, and they are characterized by different rated powers and efficiencies. {C, D} are two gas boilers that might be useful to build up backup capacities. {Z} indicates that transformers with different efficiencies could be used. Of course, all other {E, F…, Y} are placeholders to show that the investment planning problem is only limited by the formulation of the problem. As discussed in the introduction, an ideal system could be changed to new (evolved) necessities at any time. To this end, the problem formulation above can easily be changed to also tell the optimal order of installation of the units {A, B, …, Z} (if needed at all). The high complexity of these binary decisions introduces a high computational effort to solve this optimization problem, but can first of all significantly reduce costs, and also reduce risks of losing profits or running units inefficiently in the future.

Challenges in optimal planning for stakeholders

On the downside, however, high investment costs and high transaction costs are an immanent problem of planning, redesigning and implementing alternative setups, so a multi-stage investment and thus a continuous improvement of such an (urban) energy system is rather unlikely. However, the necessity to reduce risks and to actually follow a multi-stage planning approach in the future can easily be argued by typical planning questions:

- Is it certain that the heat demand decreases as anticipated, or can more customers be attracted?
- What is the future market power of large GenCos, and how high is the impact of renewable energy sources on stock market prices for electricity?
- Will prices for carbon certificates drop, rise or stay on the same level?

As becomes clear by these questions, they often remain unanswered, but are of high strategical relevance. Decision-making has become challenging due to many ongoing political and societal changes. Especially in the context of the energy transition, as well as carbon emission reduction targets have often been missed by EU member states, investment in a certain technology or generation asset is a risky and far-reaching business decision. Consequently, an architectural platform is presented in this paper that helps to tailor the future generation mix to arbitrary future necessities – be they regulatory, societal or technical.

SUGGESTED SYSTEM ARCHITECTURE

In this section, a technical system architecture is presented as a conceived concept for future energy systems integration. Thus, the proposed architecture is built on three main pillars: modularity, scalability, and standardization, which is visualized in Figure 2.

System overview

In this way, the system architecture is planned to supply electrical power to the electric grid (bidirectional power flow – **A** in Figure 2), and thermal power to a district heating network (Unidirectional power flow – **B**), while it is constituted by several classes of conversion and storage units (**C**). Accordingly, the conversion units are divided by the conversion type, which is conveniently defined by the physical input-output connection to a certain energy carrier. Thus, for example, units of combined heat and power (CHP) are classified in a first conversion class, while a group of power-to-heat (P2H) units, even from different manufacturers, are set in a second conversion class etc. Meanwhile, the energy storage units are considered as storage classes, constituting then, together with the conversion classes, a unit portfolio.

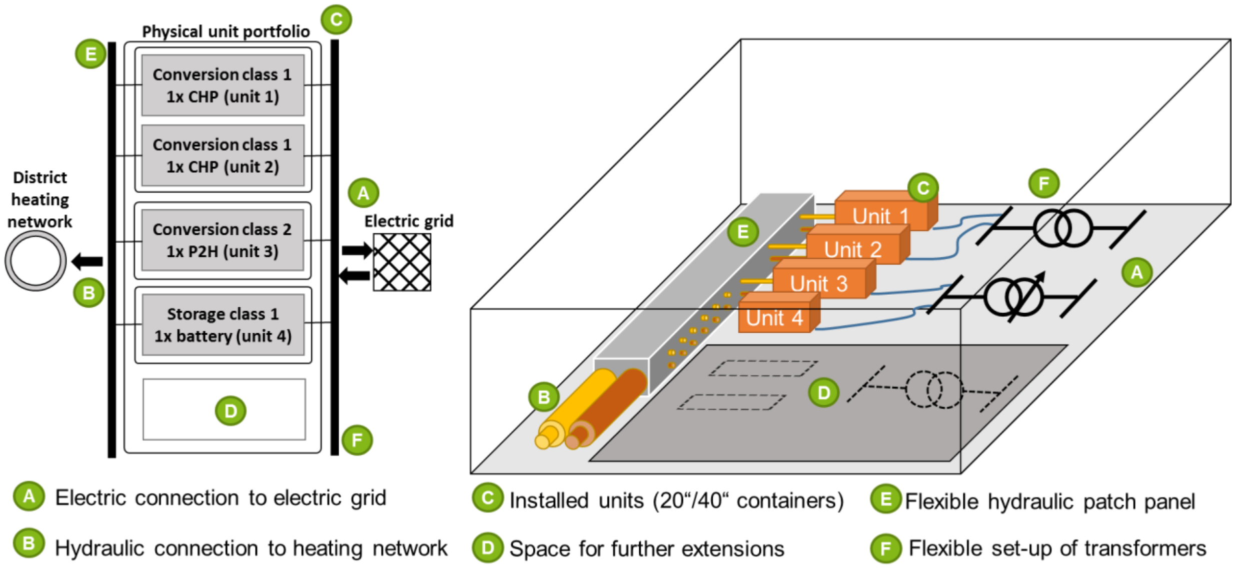

Figure 2: Developed modular, scalable and standardized infrastructure, presented as an exemplary floor plan (not to scale) [4]

It is important to highlight that such an integrated power generation facility is likely to require significant changes, retrofits or upgrades over its lifetime, as it can simply not be optimally planned and designed today for an uncertain future. Hence, the proposed system architecture must be highly adaptable to all minor and major future changes, without introducing additional costs. To this end, a flexible expansion capacity is considered in the architecture with the requirement of a reserve space (**D**). Moreover, an effortless reconfiguration of hydraulics by patch panels (**E**) must be available, as well as the reconfiguration or upgrade of the electric connection to the main grid via a bus bar and an appropriate transformer (e.g., higher rating, OLTC capabilities or other requirements, **F**).

Fast and efficient replacement of units

In all the cases the modularity and scalability are supported by the standardization of conversion and storage units. As a consequence, the system architecture requires that all conversion and storage units have to be packaged in standard intermodal container (i.e., 20 or 40 feet freight containers). Furthermore, these containers must come with standardized sockets and connectors for electric and thermal connection so that a quick installation or even reconfiguration is enabled. Currently, for example, it is already possible to find commercial small- and medium-scale CHP units, battery systems and even thermal storage encapsulated in these intermodal containers, because the prefabrication and transportation is facilitated by such a design. If more changes to a unit portfolio are expected in the future, and a faster response to regulatory and economic conditions is sought-after, then it can only be economically favorable for the planning and decision-making to follow the same paradigm for the entire installed stock of conversion and storage units.

Operational flexibility

The architecture is envisaged with a flexible scheme for the hydraulic and electrical integration into the district heating system (DHS) and the electric grid respectively. Thus, a reconfigurable hydraulic setup box is used to allow an operation mode controllability. For example, the use of current commercial controllable valves and/or low loss headers can technically provide a desirable adaptability through serial, parallel and/or mixed hydraulic arrangements based on the needed interface between the conversion units and the DHS.

Regarding the electrical integration, this must be flexible to different mixes of conversion and storage units and be able to work under more than one operation mode. Thus, for example, the units can operate as generators, loads, an in-feed or even like neutral elements. Therefore, the electrical interconnection point must keep a reserve capacity and, depending on the regulation, use a proper power transform (generator step-up transformer - GSU, for instance a transformer with on-load tap changer – OLTC). It is important to highlight that the proposed conceptual system architecture is envisioned for a wide range of possible unit portfolios, so a specific optimal design of a portfolio is not named in this paper.

In future, it would be required by vendors to follow certain standards and specifications for newly issued products. Obviously, once this has been achieved, every conversion unit and every storage unit can in fact be replaced at will at any time. This way, the realized local energy system is close to a modular puzzle, where retrofitting and optimization of the supply portfolio can be done in (arbitrarily) small steps and manageable magnitude. This is equally true for the portfolio as well as for the operation. Consequently, optimality of the entire energy system can be ascertained along the current planning horizon and in future.

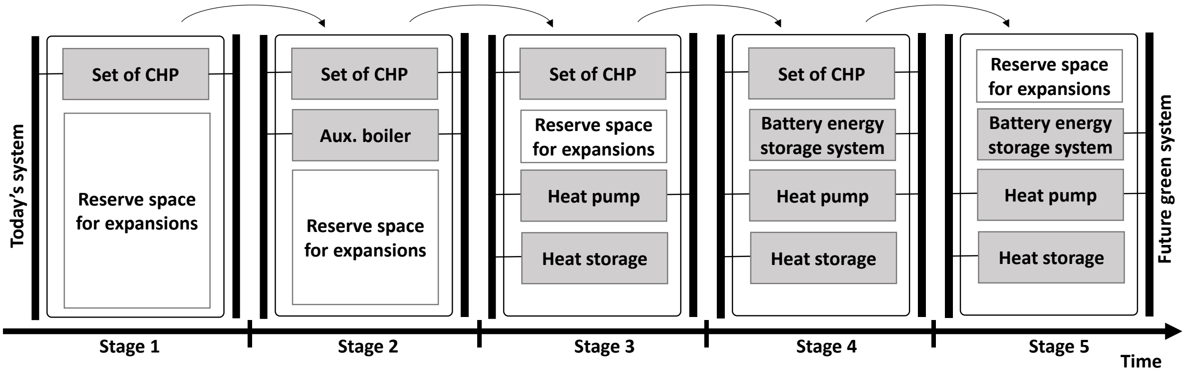

Figure 3: Example of successful multi-stage retrofit, which is enabled by the suggested system architecture

STRATEGICAL ADVANTAGES OF THE SYSTEM ARCHITECTURE OVER TIME

A hypothetical example of multi-stage planning and management of an energy system is shown in Figure 3 and discussed below. In this case, the architecture is optimally adapted in five stages. Stages do not need to be equally long, so one stage might comprise a few years or even a decade.

The initial optimal system (stage 1) starts with a typical set of CHP units to supply a district with heat and electricity. As more customers get attracted (stage 2), the heat demand of the district increases as well, and an auxiliary gas boiler is commissioned as a short-term solution.

However, in the meantime (stage 3), global prices for CO2 certificates have risen significantly, and an investment in a more environmental friendly heat pump is therefore made. As a consequence of unfavorable operation prices, the auxiliary boiler gets decommissioned in the same stage.

In stage 4, a battery energy storage system is installed as an electric power reliability enhancement strategy, and because of intermittent generation of renewables in the power system.

Finally (stage 5), as a consequence of a (again hypothetical) national emissions reduction strategy, the high penetration of renewable energies in the electric grid renders it possible to avoid combustion-based systems. As the CHP units have almost reached their technical lifetime, the decision to decommission the CHP units is sensible and economic.

While only being hypothetical, this example proves continuous change of optimality in the unit portfolio and the convenience of multiple adaptations.

DISCUSSION AND CONCLUSION

Building on interchangeable modules makes this architecture the perfect test bed for arbitrary technologies in the short term, but also avoids sunk investments for generation, because scaling and reconfiguration is simpler than for conventional generation. So, a transition from conventional generation over small-scale CHP units towards 100% renewables can be achieved step by step guaranteeing sustainable bridging system realizations over all stages. Each stage can be planned and realized in a cost-effective way while keeping the whole system architecture technology independent and open to future developments. Especially, if one technology falls short of expectations, it can simply be decommissioned or replaced. In contrast to large-scale electricity generation based on coal or nuclear power, the platform makes energy conversion and supply a "no regrets" test bed, because the means of managing investments are greatly enhanced by building on the scalability of all involved technologies. This can even avoid sunk costs. So while the openness to different vendors and technologies might seem to complicate the energy supply at first sight, the opposite is true: it is first of all the requirement for keeping the supply optimal in future. Furthermore, easy and continuous corrections are a must for the cost efficient management of the energy system.

In summary, this architecture in fact tackles typical real world problems in planning: municipal utilities seek new possibilities to bring in their expertise in this field and to guarantee cost-effectiveness of their systems despite continuously decreasing heat demand (due to e.g., home-owners who retrofit their dwellings).

The interested reader is also referred to [4] for a more detailed explanation of many elements and an outlook.

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