Article

Adaptable Energy Systems Integration By Modular, Standardized and Scalable System Architectures: Necessities and Prospects of Any Time Transition

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Abstract: Energy conversion and distribution (heat and electricity) is characterized by long planning horizons, investment periods and depreciation times, and it is thus difficult to plan and tell the technology that optimally fits for decades. Uncertainties include future energy prices, applicable subsidies, regulation, and even the evolution of market designs. To achieve higher adaptability to arbitrary transition paths, a technical concept based on integrated energy systems is envisioned and described. The problem of intermediate steps of evolution is tackled by introducing a novel paradigm in urban infrastructure design. It builds on standardization, modularization and economies of scale for underlying conversion units. Building on conceptual arguments for such a platform, it is then argued how actors like (among others) municipalities and district heating system operators can use this as a practical starting point for a manageable and smooth transition towards more environmental friendly supply technologies, and to commit to their own pace of transition (bearable investment/risk). Merits are not only supported by technical arguments but also by strategical and societal prospects like technology neutrality and availability of real options.

Keywords: energy infrastructure design; system architecture; energy transition; district heating systems (DHS); energy hubs; distributed multigeneration (DMG); multi-energy systems (MES); urban energy systems (UES); community energy; societal prospects

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1. Introduction

Many countries show a high heat demand [1] which goes along with significant carbon emissions. One means to decarbonize the heat supply is given by more efficient combined heat and power (CHP) approaches. While CHP is one specific technology that integrates heat and power delivery, other grids can be considered for integration as well: For instance, natural gas can be stored in pipelines with neglectable losses, while electricity can be transmitted efficiently over long distances. As lower costs for generation, storage and electricity network expansion are likely, the integration of different energy systems has recently received a lot of intention.

However, despite thinkable benefits, planning of integrated energy systems generally involves a high level of uncertainty concerning future demand, prices and regulation. Uncertainty thus translates into financial risk and threatens the profitability. Naturally, risk-averse investors do favour simpler projects with a guaranteed profitability. Therefore, only few integrated systems have actually been implemented in the real world.

Looking into the profitability of planned projects, the analyses often build on tight calculations. [2, 3] For instance, the return on invest is often low while payback times are found to be high, even if

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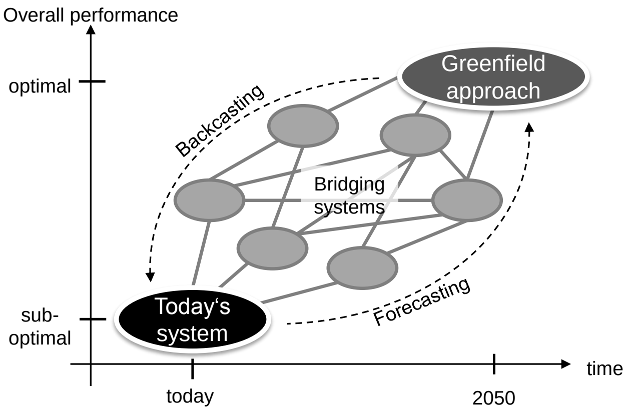

Figure 1. Vision of transition paths to final greenfield optimality, adapted from [6]

additional business cases like the provision of operating reserve to connected grids from such systems is considered.

One way to deal with uncertainty is the application of portfolio theory [4] and a thorough consideration of risk scenarios. However, in an ideal world, uncertainty would be managed by implementing new technologies in small portions, i.e., incrementally. As time progresses, energy demand, prices and regulation do not only evolve over time but do also become more assured. This way, the (remaining) riskiness of the (remaining) project is reduced successively by growing know-how and expertise from the parts already implemented, and by diminishing uncertainty of the business case. The course of implementation can thus be changed by the management, so that the final realization might differ from the initially projected system. This way of managing a business by gradually learning from actual realizations of uncertain parameters is called *real options management*, and a successor of *multi-stage investment*. Multi-stage investment into integrated energy systems and the consideration of real options have been successfully proposed and applied in case studies. [5] Besides, many other researchers have stated and analyzed the necessity to deal with intermediate steps to improve systems step by step. Especially, the term *bridging systems* was presented in the context of planning and realization stages of integrated energy systems in [6] (Figure 1).

However, in reality, both the vision presented in [6] and the case studies analyzed in [4] and [5] remain theoretic for the following reasons: investments in generation capacity are characterized as large-scale infrastructure projects, which are defined by high capital intensity and long investment periods (e.g., depreciation times of 50 years for large power stations). Most strikingly, such an investment is normally neither scalable nor separable. While the lack of scalability means incremental investments are not possible, inseparability also means the entire investment has to be done by one investor. So, the current situation in investment planning for energy supply is best described as *all-or-nothing* and *atomic*.

To this end, this paper will contribute with a suggestion of tangible guiding principles that will render a step-wise and thus more feasible transition possible. The conceptual architecture is best thought of as an infrastructure platform. Once this platform has been implemented, different supply technologies can be integrated successively. Therefore, the proposed architecture involves a paradigm change for future planning and optimization of energy supply.

In this work, we mainly address (among others) municipal heat suppliers, district heating system operators and policy makers to propose a novel technical system architecture. This architecture is meant to function as a cost-effective enabler of arbitrary transition paths for the physical implementation of energy supply.

To summarize it, the main contributions of this paper are thus:

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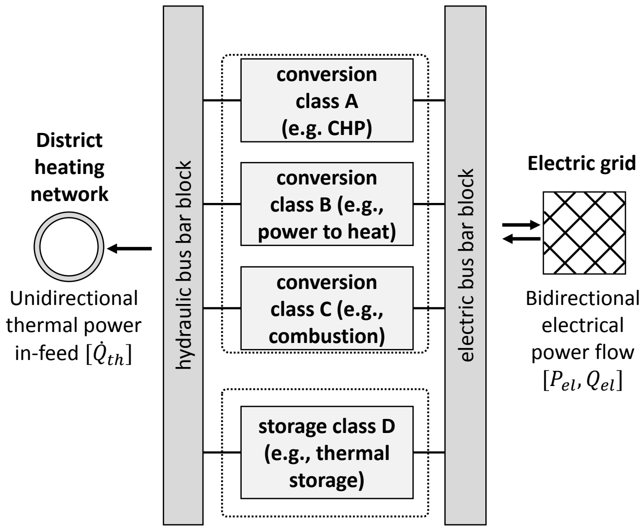

Figure 2. Abstract perspective on key elements of the architecture: energy conversion and storage units are modularized and can easily be snapped into the platform to connect to different networks

- A technical concept building on modularity, standardization and scalability is presented at a helpful level of abstraction but including detailed notes on implementation. (section 2)
- The notion of adaptability is introduced in the context of sustainable energy infrastructure. (section 2)
- A case study shows an exemplary system's evolution, which is enabled by the presented architecture. (section 3)
- Positive technical, strategical and societal prospects are discussed. (section 4)
- The connection to other concepts and visions of energy systems integration is shown to highlight compatibility and thus direct implementability. (Appendix)

2. Envisioned technical system architecture of future infrastructure and supply

This section presents the developed concept of future energy systems integration. Although generally adaptable to other energy carriers, the presentation in this paper is focused on the provision of heat and electricity in proximity to the customer.

2.1. Overview of basic elements of the architecture

As shown in Figure 3, the system comprises different **classes of conversion and storage units**. Conversion units are classified by the type of conversion, which is their input-output-connection of different energy carriers. For instance, combined heat and power (CHP) is one class of conversion units as these units convert natural gas into heat and electricity. An electric heat pump, however, can be characterized as belonging to another such class, because electricity is converted to heat. Other classes might not include a direct conversion, but store energy by charging and discharging. Such elements are included in the classification.

In reality, the realization of conversion classes is achieved by installation of physical conversion units. Of course, a mix of different conversion units from different vendors might still belong to the same class of conversion units. Naturally, this architecture does not require the installation of certain classes or even conversion units. So, the mix of conversion units can be chosen by the corresponding system integrator. Note that a mix of conversion and storage units is also referred to as a **unit portfolio** (or even portfolio in short).

As discussed in the introduction, even if a certain unit portfolio is envisioned for the future (Figure 1), it is possible that significant changes have to be made to the installation. To account for

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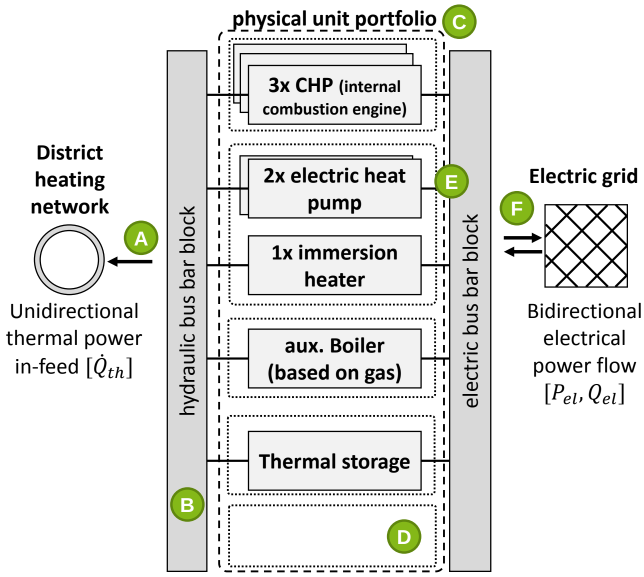
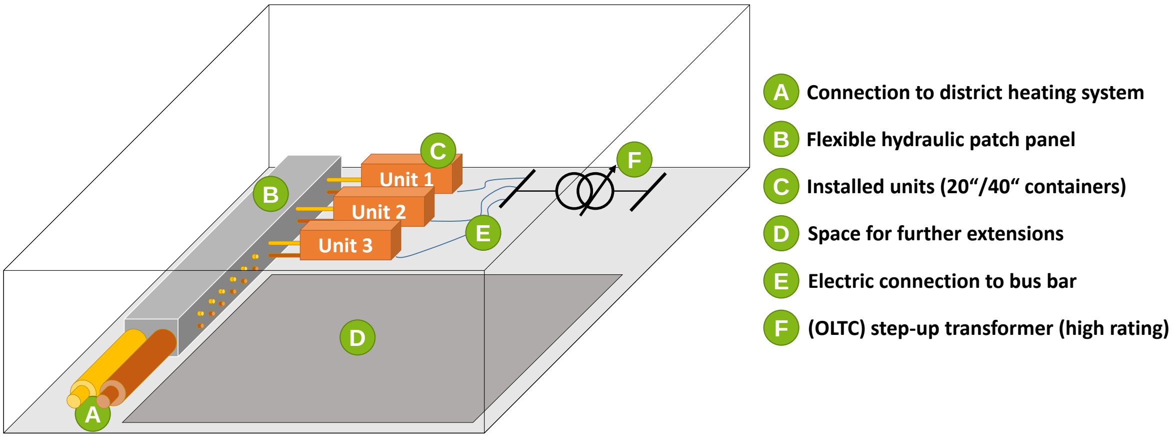


(a) Exemplary specific configuration of a unit portfolio with different technologies being modularly integrated



(b) Floor layout indicating one practical implementation of the system architecture (not to scale)

Figure 3. Overview of system architecture with thinkable, fully optional modules (none mandatory, all to be implemented at will and at any time)

this inherent management flexibility, the architecture also requires that a significant share of the space within the physical platform is devoted to future extensions or changes.

All units are therefore connected to the distribution infrastructure. The chosen portfolio is able to cover a given electrical and thermal supply task. On the left hand side of the conversion units (both in Figure 2 and Figure 3), there is a bus bar like hydraulic configuration box that is itself directly connected to the district heating network (DHS).

On the right hand side, we find the system block for the electric connection. As for conventional generation in huge central power stations, it is likely that a generator step-up transformer (GSU) behind the busbar interfaces the station and the electric grid (Figure 3b).

In this conceptual systems perspective, it is assumed that *all* available conversion units are connected to both networks, i.e., electricity and district heating. Some units might additionally be connected to another supply like gas mains, but the explanations here focus the supply perspective and thus omit such energy carriers for easier comprehension.

So, once the system has been set up it is able to provide heat $[\dot{Q}_{th}]$ to the district heating system, and to provide electric power $[P_{el}, Q_{el}]$ to the electric grid. While heat cannot be consumed from the grid ($\dot{Q}_{th} \overset{!}{\geq} 0$), it is possible to convert electric power to heat by using corresponding conversion units. In this case, $P_{el} \leq 0 \wedge Q_{el} \leq 0$ is possible as well. For instance, electric heat pumps and immersion heaters consume electric power to provide heat.

2.2. Physical modularity and standardization of conversion and storage units

Even today, small- and medium-scale CHP units are situated in intermodal containers. But in fact, there are many more energy-related systems which are encapuslated in intermodal containers, e.g., battery energy storage systems, thermal storage, and even static synchronous compensators (STATCOM). These containers are known as 20 or 40 feet freight containers [7]. The advantage of such a packaging is given by the easier transportation to the final destination by trucks, and by the standard equipment for handling them by cranes. This decreases costs for both decision-making and handling of novel conversion units. [8]

If each unit is packed into a container, then one (conversion or storage) unit equals one module. In contrast to current practice, it is therefore mandatorily required by this architecture that all units are actually encapsulated in intermodal containers with identical hydraulic and electric connectors. As a consequence, installed capacity and quality of supply can easily be controlled by installing additional modules. Besides, it is also possible to replace or decommission them at any time because handling and transportation is so easy. Modularity therefore also translates into *scalability*, which further facilitates planning and integration.

2.3. Integration into the electric grid

As the actual mix of conversion units is not specified but depends on the specific economic and environmental conditions, the entirety of conversion units can act as a load, as an in-feed or as a neutral element at the interconnection point with the electric grid. As the successive fine-tuning of the generation portfolio should not restrict the modes of operation, a sufficient electric connection is necessary. As this paper is meant to propose a certain architectural thinking, exact numbers are not named here. Instead, it is suggested to keep future changes of requirements in mind when setting up the platform for the first time, so in general, the connection (right hand side in Figure 3) should bear a certain reserve in capacity for the most likely (i.e., already anticipated) future development to be called sufficiently large.

First of all, congestions by thermal and voltage limits of the lines should be circumvented by connecting to a sensibly high (available) voltage level. Using an independent feeder might also help mitigate line overload and interaction with other loads. Depending on regulation, it might be required from the DSO or TSO to equip the generator step-up transformer (GSU) with on-load

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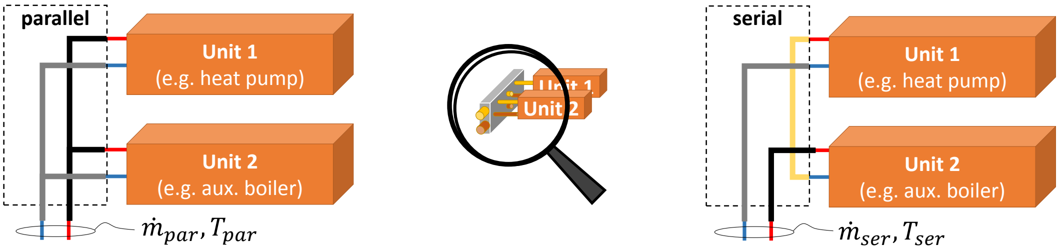

Figure 4. Example for flexible configuration of the hydraulics

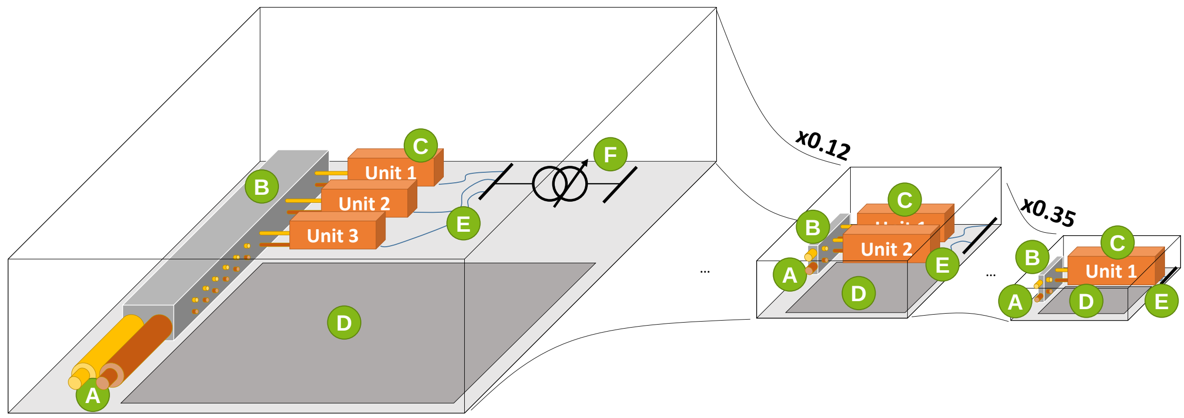

Figure 5. Three examplary configurations as a response to different spatial requirements indicate general scalability and universality of the system architecture

tap changer (OLTC) capabilities to react to voltage deviations or reactive power requirements at the interface between station and electric grid.

Again, these considerations depend on the specific case. By committing to the above principles, the inherent flexibility of the conversion units to provide active and reactive power to higher voltage levels can potentially be used in the future. This can come in hand as big (inert) generators are successively disconnected from the grid, and ancillary services have to be provided by a mix of different controllable supply technologies including intermittent generation from renewable energy sources.

2.4. *Hydraulic integration into the district heating system*

The freedom of controlling the mode of operation in the future is also necessary for the supply of heat: A reconfigurable hydraulic setup box is used to allow serial, parallel and mixed configurations depending on the current necessities (Figure 4). The hydraulic setup is deliberately treated as a black box model. Its purpose is to ascertain the compatibility of different conversion and storage units by providing an interface to the DHS that works independent of qualities like temperatures and mass flow rates. The necessity is especially given if there are different kinds of conversion units [9].

The ability to reconfigure the units' thermal input and output ports is an important feature for future replacements of individual units. However, the feature is also beneficial to cope with seasonal changes of the supply temperature (which is driven by ambient temperature), and by changes in the (spatial) load distribution. Hence, such reconfigurations are likely to happen multiple times per year.

Technically, these requirements can be fulfilled by a system of controllable valves and/or low loss headers. Both elements are readily available for different ratings and other design parameters.

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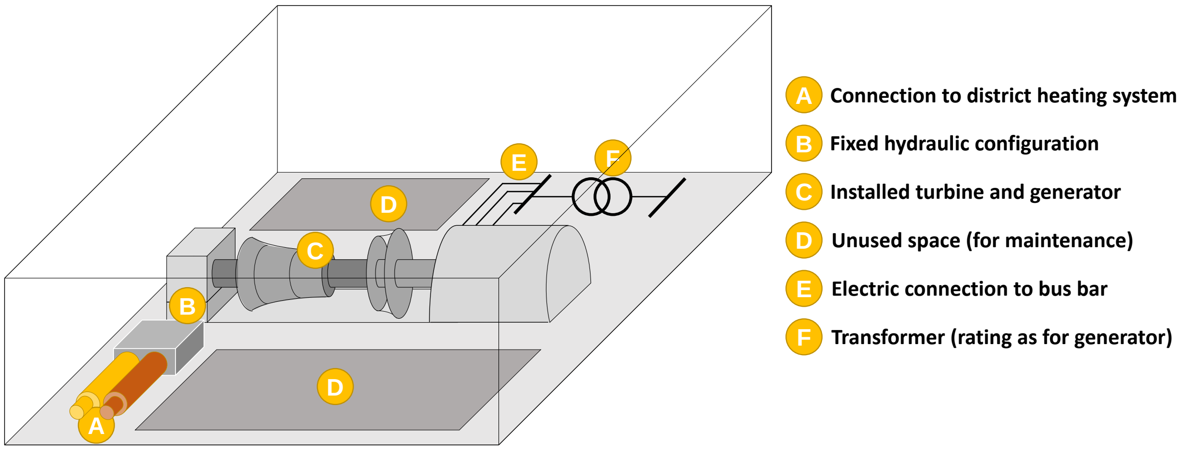

Figure 6. Typical combined heat and power generation based on a steam or gas turbine and a generator

2.5. Spatial integration into the urban built environment (spatial planning perspective)

The floor plan in Figure 3b is a rather large example of existing heat station facilities. However, many cities do in fact comprise brownfields with good connectivity to electric grid and DHS. As they might be found in different locations, and in differing qualities and sizes, the general applicability for arbitrary available brownfields is visually indicated by Figure 5. It shows three floor plans which differ significantly in size while still maintaining the most important features of this architecture. The hereby proved scalability of the entire platform also indicates the possibility to split the system if necessary. For instance, if multiple units are needed to cover the local heat demand, but there is no facility available that offers enough contiguous space, then a higher number of (semi-)distributed facilities can be set up instead of a central one.

To sum it up, this architecture requires to stick to the maxim of adaptability. Consequently, easy reconfiguration of the hydraulics must be possible, units must always come in intermodal containers, and extra space should be allocated for future extensions or redesign.

3. Exemplary hypothetical evolution of a realized system over decades

It is assumed that a given turbine-based energy supply lacks cost-effectiveness and is thus scheduled for decommissioning. Figure 6 shows a corresponding large-scale CHP unit as it is typically found in many DHS. As soon as the facilities have been reworked according to the suggested architecture (Figure 3b), the former heat and power station has the function of an infrastructure platform. From now on, (future) supply systems can be implemented at will.

In Figure 7, the example is broken down to five devised stages. It is furthermore assumed for this example that each of the assumed stages lasts for six to ten years, so an evolution over, e.g., 30 years is shown.

The first transition of the system is a typical **starting point** (Figure 7a) that is highly realistic for today's urban energy supply. By building on three block-type CHP units and an auxiliary boiler, the implemented system is fully compatible with the requirements of the architecture, and the units are in fact cost effective in today's price and regulation regime.

In a **second stage** (Figure 7b), the national government has set up a fund for projects that build on geothermal heat. Therefore, in this stage, a drilling project has succeeded, and an two electric heat pumps are commissioned.

In the **third stage** (Figure 7c), the heat demand of the stock of urban buildings has decreased significantly due to strong modernization efforts by different institutional real estate investors. Consequently, the auxiliary gas boiler (with the highest specific heat prices) is decommissioned.

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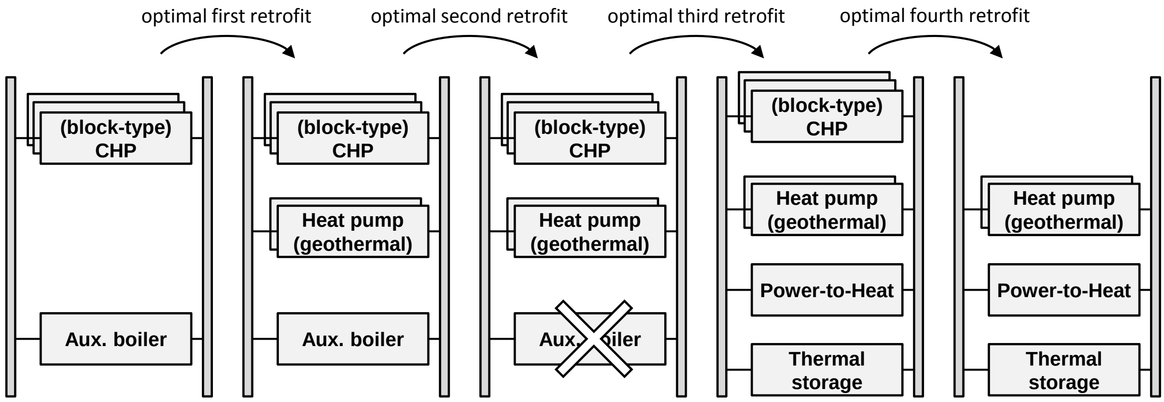

(a) Stage 1 **(b)** Stage 2 **(c)** Stage 3 **(d)** Stage 4 **(e)** Stage 5

Figure 7. Assumed evolution of a configuration over years and decades

The **fourth stage** (Figure 7d) builds on the assumption that numerous big generators are now missing in the electrical grid. Therefore, the capacity prices for ancillary services have been increased dramatically, and an investment in power-to-heat and thermal storage is finally favourable. Costs are covered by a market driven operation that takes into account the revenues from operating reserve while covering the heat demand.

In the **final stage** (Figure 7e), it is furthermore assumed that two effects once again change the optimal unit portfolio: On the one hand, the carbon taxation of fuels (i.e., natural gas) has been increased by a new ordinance for environmental reasons, on the other hand, the integration of generation from RES has progressed significantly over the past years. Of course, with the previous investments into additional installed capacity, the CHP units are obsolete now, and their operation is not cost effective. As a general overhaul is due, they are simply decommissioned, uninstalled, and not expected to be replaced.

This sample story is able to once again highlight necessity and change of optimality (as opposing to greenfield optimality assumed in [6], and discussed above), and it shows how the adaptivity of the system architecture is enabling efficient reconfigurations whenever needed.

Of course, initial retrofitting of existing facilities, or erection of the platform respectively involves (additional) up-front costs. To argue the necessity of implementing the proposed architecture, different advantages of an implementation are argued from a highly conceptual and thus more abstract perspective in the following section.

4. Technical, strategical and societal prospects of the introduced adaptability

In subsection 4.1, the meaning and foundation of *adaptability* are discussed in the context of energy supply. Based on this concept, the added value brought by the infrastructure is argued in subsection 4.2 to subsection 4.5. Afterwards, thinkable actors that might benefit from such an investment are presented (subsection 4.6).

4.1. Adaptability as an indicator for the sustainability of systems

The value proposition of this architecture is best described by the word *adaptability*. Therefore, the following Definition 1 following [10] shall be used:

Definition 1 (Adaptability)**.** *Adaptability is the quality of being able to adjust to new conditions.*

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Table 1. Analogy to factory transformability features

	Key element of this architecture	**Note on physical implementation**	**Changeability enablers** [11]	
Adaptability	Scalability, Modularity	Block-type units in intermodal containers (as defined in ISO 668 [7])	Scalability Modularity Mobility	Transformability
	Standardization	Hydraulic matrix setup and electric grid connection	Compatibility	
		Defined connectors and outlets for all units		
		Inherent feature of electric power and heat (commodities)	Universality	

In the context of energy systems, the notion of *adaptability* involves the adjustability of (1) the (original) configuration of conversion units, (2) the specific operation, (3) the use/value that is brought by the operation of the system.

In fact, *transformability* was identified as a key element in factory planning [11]. The authors also identify certain enabling elements that have to be followed to ascertain transformability (in analogy to the suggested adaptability). These are called *changeability enablers* and comprise universality, scalability, modularity, mobility, und compatibility. The analogy to a factory as an infrastructure can thus be used to additionally discuss the architecture from factory planning perspective.

Following Table 1, it becomes clear that all aspects of *transformability* suggested in [11] have been implemented by the platform. However, it also becomes clear that key concepts from factory planning cannot be copied and applied one by one. Instead, a mapping is necessary, e.g., *standardization* is best argued by *compatibility* and *universality*, and the physical implementation even comprises three different aspects. Interestingly, the aspect of *mobility* is covered indirectly because of the mandatory use of *intermodal containers* although it is not even a key element of this architecture.

Building on this adaptability, four categories of added value can be identified, which are used to structure the following discussion:

1. Lower cost of redevelopment and redesign,
2. lower cost of installation and system integration,
3. compatibility with future markets, and
4. local concentration, economies of scale and continuous controllability.

It should be noted that these categories are not mutually exclusive. Instead, they support one another and are interdependent. Figure 8 depicts the hierarchy of enabling elements of the architecture and prospects for a system operator on a high level of abstraction.

4.2. Lower cost of redevelopment and redesign of portfolios

As soon as the proposed architecture is realized, it acts as a platform for future evolutions of conversion and generation. Changes to the portfolio can then be done at relatively low cost. However, each stage of redesign or optimization still has to be planned and calculated. So, the costs for planning and designing future (successive) systems rather depend on the availability of software tools and engineering knowledge in the field of energy systems.

Compatibility to numerous fields of research and existing system descriptions is in fact given (cf. appendix for details). This includes *multi energy systems (MES)* [12], *distributed multi generation (DMG)* [13], *the energy hub* [6,14], and *urban energy systems (UES)* [15]. Therefore, all simulation and optimization tools and studies that deal with optimal design, placement, operation, or market integration can be reused, which is an important feature to ensure low planning costs.

For instance, to connect to the introduction, the case studies in [4] and [5] were conducted with energy hub and MES in mind. However, both approaches remain on a high abstraction level where the installation of additional units is directly possible. So, it was not discussed in their contributions if their optimal design is actually technically feasible, or if spatial constraints hinder the optimal implementation. In addition, even if technical feasibility was given, it is likely that high transaction

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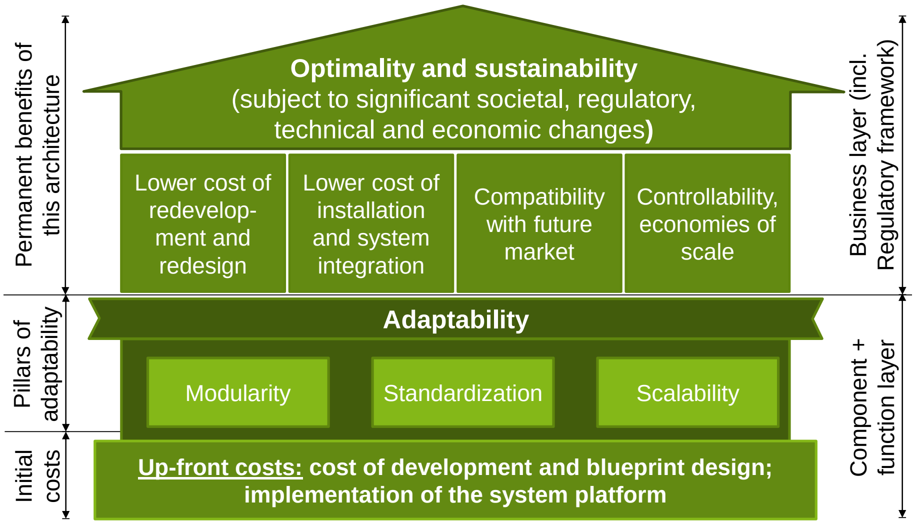

Figure 8. Conceptual view on the hierarchy of enabling elements of the infrastructure and derived benefits of an implementation

costs would have been involved for an actual realization. Consequently, the here proposed architecture builds the foundation for both case studies to be rolled out in practice, and supports their optimization approaches with practical evidence of applicability, which is a strong contribution.

4.3. Lower cost of installation and system integration

A reference case for comparison is given by decentralized installation of the same equipment in individual buildings (e.g., hospitals, residential buildings, office buildings). Due to the diversity of conditions found in buildings, which means the siting in the given space, the procurement of additional components, and even the wiring thereof has to be tailored to the conditions and expectations of the individual customer then. According to [16], this system integration accounts to additional 39 % to 76 % of the module cost of block-type CHP units alone. These costs do not even include planning, expert's reports or the request for bids (in a public bidding process). So, the sum of all these expense factors renders a significant share of all projects uneconomic.

However, as soon as the proposed architecture is implemented, these costs are significantly reduced. The same is true for the installation since all modules can be transported at low costs.

4.4. Long-term market compatibility

4.4.1. Access to new markets

As procurement prices differ for energy depending on the sales volume of the customer, bulk buyers have a competitive advantage in contrast to, e.g., domestic customers. According to [17], this is one of the main reasons why distributed CHP units for smaller buildings are often not cost-effective. Consequently, they depend much more on subsidies.

With this architecture, this competitive advantage is maintained, i.e., procurement of natural gas is relatively low despite the use of the units typically found for smaller scale application. In addition, certain markets are only available with a certain market power, e.g., spot markets and over-the-counter trading for electricity are possible due to the aggregation of generation capacity.

4.4.2. Market compatibility by fit: Generation capacity and quality

If long-term market compatibility shall be guaranteed, an increase and decrease in generation capacity must be possible in the short- to medium-term. Due to the high stress of the ICE of many

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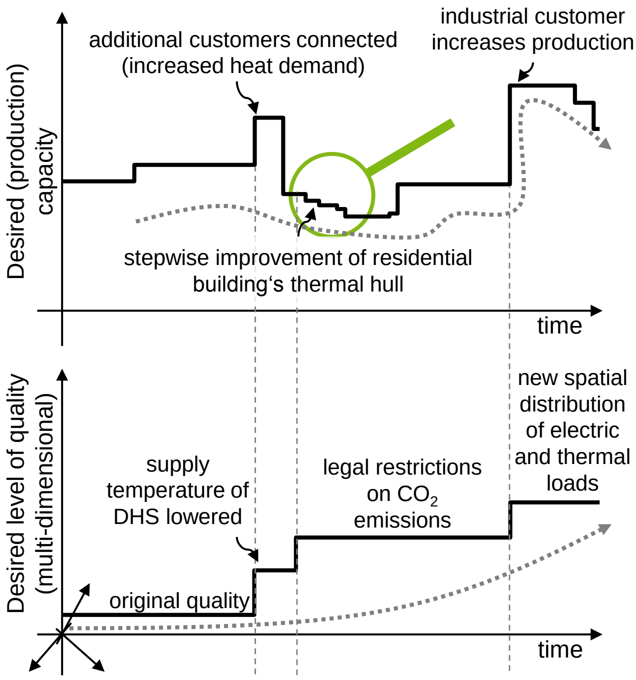

Figure 9. Qualitative difference between pure generation power and the associated quality of supply (deliberately without time and capacity scale)

CHP units, a revision or general overhaul is required every 25.000 to 35.000 operating hours [18]. Consequently, for this exemplary technology, a transition towards a different stock of units change might be possible every five to seven years (at 5.000 full load hours). In practice, for a given mix of conversion units, it is likely that even in short term one unit is due for replacement. This is a direct consequence of the modularity.

Another advantage that can be drawn from the modularity is the changability of quality of supply. For instance, regulators might introduce a legal limit on thermal losses or emissions of carbon dioxide equivalents, or even the level of noise emissions. As the combined (electro-thermal) supply task in the urban built environment changes continuously [19], the ratio of electric and thermal power output (i.e, the electric CHP coefficient σ_{el}) can be manipulated by switching to a different technology.

Every single requirement discussed above might generally add another dimension of quality. So, the notion of quality is much more extensive than the examples above, and it can be argued that the desired level of quality (although abstract) can generally be expected to increase. A visual concept of the dimensions of capacity and quality can also be found in Figure 9.

4.5. Local concentration, economies of scale and continuous controllability

4.5.1. Local concentration and economies of scales

This architecture recommends to use the highest available voltage level, which can be any voltage level starting from low voltage (LV) though. However, even in this worst case scenario the bundling of conversion units to one facility leads to low costs for information and communication (ICT) and metering. If medium or high voltage grid are available for connection, all advantages of the centralized generation are maintained for this architecture. Please note that the comparison has to be drawn with a fully decentralized energy supply, which involves, for instance, rooftop PV and CHP units in the basement of buildings. Naturally, the fully decentralized scheme involves higher costs.

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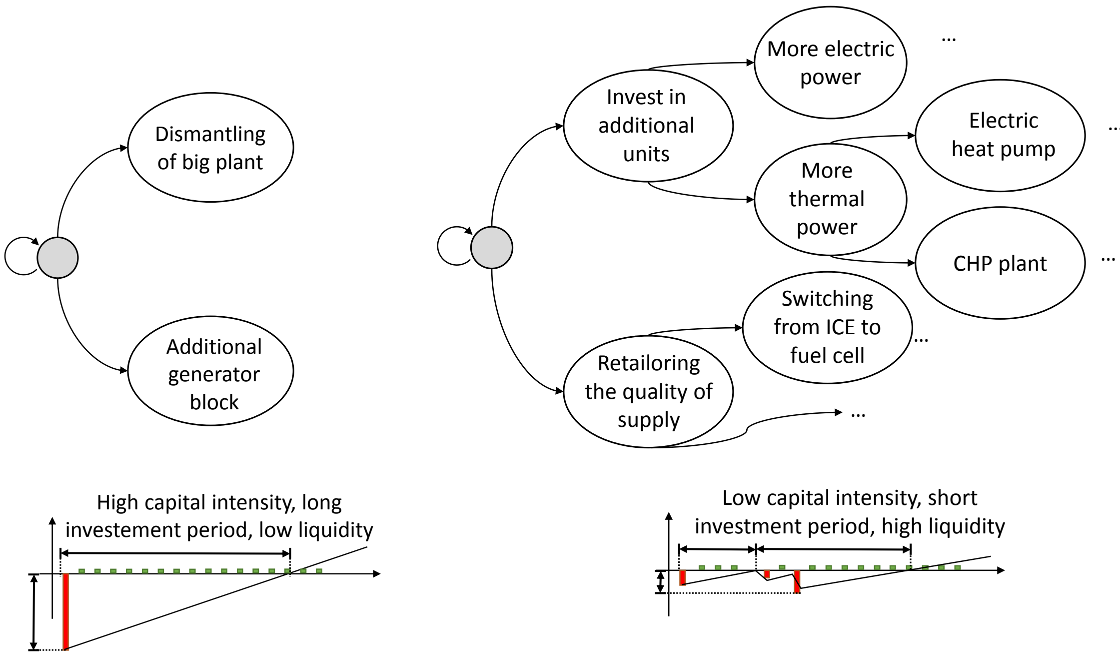

(a) Conventional generation: few real options, low liquidity

(b) This architecture: many real options, high liquidity

Figure 10. Availability of real options may inhibit (left) or support (right) the adaptability of a portfolio, and affects the quality of the associated investment cash flows (investment period and capital intensity)

The improved market access discussed above can also be argued as part of the *economies of scales*, and different economies of scales can be identified in the fields of public bidding processes for new generation units, technical personnel (for maintenance), and in operation (and optimization thereof).

4.5.2. Continuous controllability by available real options

The continuous responsiveness to changes in the desired quality or capacity of supply can also be understood as a the provision of real options. There are numerous thinkable changes to the installed base of conversion units, as indicated in Figure 10. This includes (but is not limited to) additional units, fewer units, different units and a changed operation of units. It should be noted that such changes are possible at any time, although probably only conducted every five to ten years. It must also be stated that the availability of these options has an inherent value even if none of the options is ever (!) called. The reason is that both actual losses and lost profits can be avoided by actively managing the portfolio of generation units.

As stated above, many CHP units must regularly undergo a general overhaul anyway, which means that the granularity of changes is high. This also helps to understand why there are more (and better) real options for this architecture available (Figure 10b) than for the case of conventional generation (Figure 10a). In addition, the more manageable size of changes directly leads to a higher financial liquidity, so both the dimension of time and corresponding financial resources can be improved.

The value of these real options can be roughly estimated by applying the methodology presented in [5] to a scenario of demand and economic conditions, but this is out of the scope of this paper.

4.6. Thinkable actors for an implementation (and business cases)

For such a platform the categories of *research*, *funding*, *ownership* and *operation* can be considered independently. Here we omit the initial research and focus on funding, ownership and operation instead:

Generating companies (GenCos) might be able to build a business case on this architecture by focusing on the by-product of heat, i.e., instead of erecting other big central generators, a certain share of the marketable electric energy might be covered locally. In comparison to the status quo, this can be thought of as cutting a portion of the current generation portfolio into manageable chunks, siting them in the urban environment (closer to heat demand), and avoiding lossy condensation in cooling towers (i.e., just feeding the DHS instead). GenCos are experts in asset management and (risk-averse) portfolio theory, so they could easily implement the system.

Municipal utilities which operate a given DHS could become trusted partners of owner-occupiers, landlords and real estate companies by offering heat and electricity which is guaranteed to be generated in an environmental-friendly way. The value proposition comes from the integration of more advanced technologies as wished-for by the customers, and the platform could serve as a local show room open to the public, so every interested customer could visit the facility to understand how the energy transition might be shaped by current and future investments into new modules.

Such a system might also be implemented as a *community energy system* [20] by an *energy cooperative*. This case is close to municipal utilities because of the interest of the customers (here: the community) to invest into a more environmental-friendly product. However, the economic feasibility might be easier to achieve due to a differing price sensitivity of involved customers: For instance, higher specific prices for heat and electricity might be accepted, and even a flat rate might be an option. Furthermore, cooperative shares might be drawn to collect money, and banks might grant further loans accepting these shares as a security.

In general, it is even thinkable that in the context of future energy liberalisation, such an infrastructure is deliberately opened to multiple parties, i.e., non-discriminatory access is provided to all actors mentioned above. In this scenario, the platform acts as a *colocation centre* (as known from data centres). This would in turn eliminate the operational challenges that go along with a provision of third party access to the DHS [21].

5. Conclusion and outlook

5.1. Summary and conclusion

Today's investment in new generation capacity is characterized by high capital intensity and long-term depreciation. Moreover, the risk of misinvestments and thus full write downs is significant due to a high level of uncertainty of demand, prices and regulation. Therefore, more efficient conversion technologies and systems (e.g., CHP and energy systems integration) are rarely implemented.

In this paper, the difficulty in finding a long-lasting, efficient and optimal mix of energy supply is tackled from the perspective of modular infrastructure. To this end, a paradigm change is fostered in planning and implementation is envisioned. This is achieved by a highly adaptable system architecture, which can in fact be used as a practical starting point by a wide range of stakeholders.

Necessity and added value were discussed in terms of technical, strategical and societal prospects. Sticking to a high level of abstraction (bird's eye view) presents the architecture's strengths independent of country and particular case study. Although strong focus was laid on the conceptual strength of the architecture, all advise remains specific. By sticking to the guidding priciples discussed in this paper, risk-averse investors can benefit from a step-wise (more scalable and thus manageable) systems integration.

Besides, to the authors knowledge, this vision of an architecture is the first practical guide on implementation of integrated energy systems (energy hubs, DMG etc.) at the community or urban/municipality level at all, which is an important contribution.

5.2. Outlook on future research

Naturally, due to the novelty of the developed architecture, neither cost-effectiveness nor exact standardization of all connectors could be analyzed and described in detail in this paper. However, as the architecture is compatible with the energy hub, a multitude of developed optimization tools in literature can be used to analyze the depicted example case as well as comparable scenarios for municipal district heating utilities. (Examples are given by [4] and [5].)

For now, it is difficult to completely assess what magnitude of adaptability should be provided today to account for future uncertainties, e.g., how much (physical) space should be left for additional units, and how high the transformer rating should be in practice. New tools thus have to be developed to find good compromises between spatial requirements, ground costs, initial investment and desirable level of adaptability (or existing tools have to be applied to this new research question). Furthermore, the standardization process for block-type conversion and storage units in intermodal containers will have to be started, which is a diligent but routine piece of work.

Despite all these necessities, the authors are confident that implementing integrated energy systems according to the developed architecture will eventually enable a faster and more cost-effective energy transition due to the enabling character of the integrated infrastructure.

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Appendix A. Analogies and connections to existing architectures, system descriptions and concepts

A lot of concepts were presented in literature to model energy systems integration and discuss its prospects (cf. [12] for a review). This section takes a look at the most important such architectures and conceptual frameworks to prove recent research in this field can easily be adopted, i.e., optimization and planning tools can be used further.

Appendix A.1. Integrated infrastructure and supply planning: Urban Energy Systems (UES)

Urban energy systems (UES) [15] were developed as a planning tool that optimizes the location of generation facilities and their connection to loads/customers. For instance, it was applied in [22] to find the optimal siting of heat stations and CHP units in an urban (i.e., densely populated) context. Here, technical non-feasibility of certain projects was considered by additional constraints in the optimization. So, actual planning restrictions were reflected in their tool.

The architecture presented in this paper has been characterized as *enabling infrastructure*. It is completely in line with the aim of UES itself. In addition, as the number of options and general feasibility is increased by its implementation, it is thus clear that certain constraints can effectively be revoked.

Appendix A.2. Local multi-carrier generation: Distributed Multi-Generation (DMG)

Another important contribution comes from the concept of *distributed multi generation* (DMG) presented in [13]. In their vision, multi generation is a widespread means implemented locally in smaller scale and in different locations. While the main goal is to cover local heat and electricity demand, certain connections are mandatory for DMG: excess heat must be injected into a DHS, a (rigid) electric grid is connected anyway, and cooling or even hydrogen network can be part of the overall system as well (if applicable). The basic idea is to require a CHP plant which can be enhanced by an *additional generation plant (AGP)*. The AGP is not specified but shall in general complement the CHP generation. It is important to note that the hydraulic configuration is explicitly discussed, i.e., the need to engineer the optimal connection is identified.

The DMG system is thus more specific with the mandatory requirement of a CHP to be installed, but generic with regard to all other (additional) technologies. It points out the same necessities for the hydraulics that have been advanced in this architecture. Again, the additional cool and hydrogen production discussed for DMG do not contradict this work at all, but can of course be implemented as well.

Appendix A.3. High level multi-input-multi-output systems perspective: Energy hub

Another concept that has greatly contributed to the understanding of energy systems integration is the *energy hub* [6]. Their idea was to develop a generalized and fully linearized system description to ease the implementation for optimizations for multiple energy carriers. Furthermore, their vision was to start with a greenfield approach to find a desirable (supposed to be) optimal solution for the future. Certain transition paths should then pave the way to approach this final solution (Figure 1).

The similarity with the proposed architecture and the DMG concept is apparent, but certain differences become clear as well: The energy hub is a much more abstract multi-input-multi-output converter system. Even the description remains highly conceptual as the actual dimension and implementation of an energy hub is left open to a potential adopter. Instead, the general implementability for buildings, production facilities, cities or other arbitrary entities is dicussed. As for DMG, one type of unit per class is considered, which is a helpful assumption for the studies of the general feasibility. However, this architecture clearly differs and advances the understanding of practical future designs of integrated energy systems by (potentially) incorporating multiple units per class. As the research of energy hubs has greatly progressed, the step towards practical implementation suggested in this paper is an important connection to current literature.

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