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A District Approach to Building Renovation for the Integral Energy Redevelopment of Existing Residential Areas

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Abstract: Building energy renovation quotas are not currently being met due to unfavorable conditions such as complex building regulations, limited investment incentives, historical preservation priorities, and technical limitations. The traditional strategy has been to incrementally lower the energy consumption of the building stock, instead of raising the efficiency of the energy supply through a broader use of renewable sources. This strategy requires an integral redefinition of the approach to energy building renovations. The joint project SWIVT elaborates on a district redevelopment strategy that combines a reduction in the energy demand of existing buildings and their physical interconnection within a local micro-grid and heating network. The district is equipped with energy generation and distribution technologies as well as hybrid thermal and electrical energy storage systems, steered by an optimizing energy management controller. This strategy is explored through three scenarios designed for an existing residential area in Darmstadt, Germany, and benchmarked against measured data. Presented findings show that a total primary energy balance at least 30% lower than that of a standard building renovation can be achieved by a cluster of buildings with different thermal qualities and connected energy generation, conversion, and storage systems, with only minimal physical intervention to existing buildings.

Keywords: building renovation; primary energy demand; smart district; micro grid; district heating; energy storage; renewable energy generation; energy management; energy efficiency

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1. Introduction and Motivation

The existing built environment embodies a large potential within the German governmental energy policy goals of halving primary energy need and increasing the ratio of renewable energy to gross final energy consumption to 60% by 2050 [1]. Buildings represent almost 40% of primary energy consumption in Germany, of which almost 70% consists of thermal energy. Most of Germany's current stock of 19 million residential buildings is, partially or not, energetically renovated. While up to 80% of their energy need could be offset [2], building renovation rates have not reached targeted goals for many years. Time-consuming planning due to cost-intensive accompanying measures and complex boundary conditions required to comply with the strict normative for energy savings ("Energieeinsparverordnung", in short EnEV) play a role in this [3]. The current ordinance allows a primary energy balance for renovated buildings of 140% compared to a reference building for a new construction [4]. The calculation of primary energy need takes into account both the quality of the thermal envelope and the efficiency of the energy supply chain, from generation to storage, conversion, and distribution. Building installations and the choice of energy systems thus play a decisive role in the evaluation of renovation concepts.

An array of different energy technologies for renewable as well as decentralized energy generation, efficient energy storage and distribution are both available on the market and being currently developed. There is, nevertheless, no integral concept for their physical connection and networked operation as a building energy system. Improving the thermal envelope, on the other hand, has proven controversial due to aesthetic limitations, problematic end-of-life scenarios (insulation creates waste with no residual value, which is also difficult to separate and recycle [5]), incompatibility with historical preservation, fire hazards, and the need for extensive modification of construction details (i.e., roof projections).

The approach developed in SWIVT, an acronym for "district energy modules for existing residential areas—impulses for linking energy efficient technologies" (in German "Siedlungsbausteine für bestehende Wohnquartiere—Impulse zur Vernetzung energieeffizienter Technologien"), focuses on entire districts instead of single buildings in order to exploit stochastic and synergetic potentials of an efficient local energy generation and distribution system. The developed approach combines interventions to reduce the energy demand of the current building stock with its physical and operational connection within a local heat network and power micro-grid equipped with energy generation and storage technologies. The district's operation is regulated through an energy-management unit called SWIVT-Controller, which optimizes energy flows through a control strategy. Thanks to the flexibilities offered by the components and the control strategy, the system can react to volatility in renewable energy generation and consumption, while optimizing energy efficiency and operational costs. The joint project, led by TU Darmstadt and developed in collaboration with University of Stuttgart and AKASOL GmbH, a supplier of lithium-ion batteries, sets the following goals: the use of technological innovations in energy efficiency for the built environment, the linking of different disciplines and actors, and the development of new methods for monitoring and energy management. Figure 1 shows a diagram of the SWIVT concept.

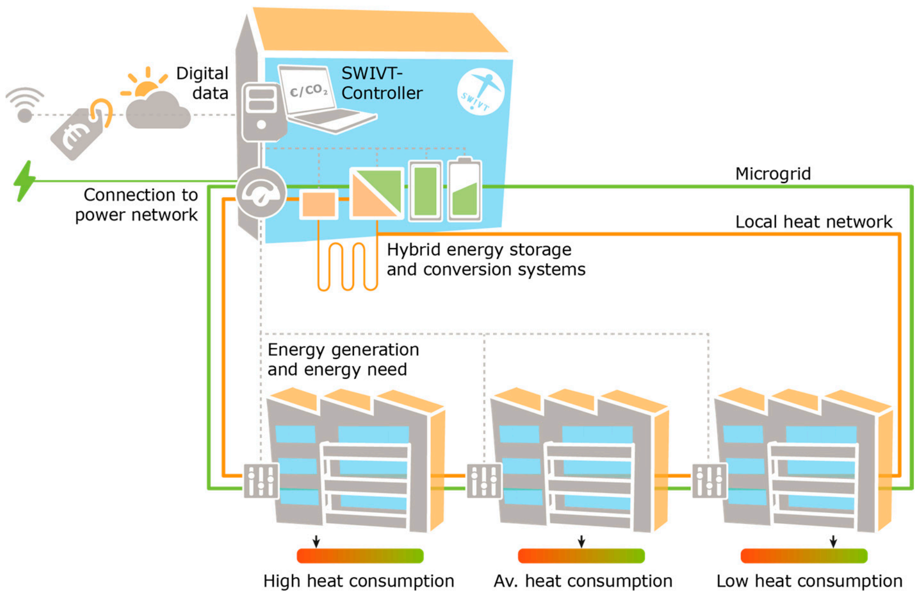


Figure 1. The SWIVT concept for energy efficiency in existing residential areas through the integration of a micro grid, district heating distribution system, energy generation and storage technologies, as well as the use of ICT.

Buildings with different thermal qualities can be connected within a district heating distribution system and supplied efficiently at different working temperatures, thus minimizing the need for renovation measures. Roofs and cellars, currently excluded from profit generation, can be rented out to the district operator for the placement of energy system components. The developed control strategy can maximize self-consumption of locally generated energy and avoid generating any unused heat, thus minimizing overall system losses. Other than selling energy to tenants, the investment can be supported by offering flexible energy supply and capacity in power markets. Thanks to better resilience of the system to fluctuations in energy availability, the share of renewably generated energy within the power distribution network can be increased without expensive conversion measures. Thanks to clustering flexibilities at the distribution level, the necessary computing power to address complex forecasts of balancing energy capacities at the power transmission level can be reduced. By introducing a new actor who sets-up, operates, and maintains the energy system of the district, energy providers can remain in the value-chain while housing companies can focus on their physical assets. The creation of a feasible investment model can help increase market penetration of innovative energy technologies, such as storage systems.

A successfully realized example of energy efficiency in existing residential buildings is the project Lichterfelde in Berlin. The buildings were renovated and equipped with energy generation and storage components, as well as an energy management unit. The system delivers a net balance of heating supply from renewable sources [6]. However, by addressing single buildings, the concept misses essential synergies, especially from the perspective of electrical energy. The role of smart districts [7] within a power network supplied by a high share of renewable energy has been explored by different research projects. In particular, the model developed for the city of Mannheim in the project "moma" foresees clusters of buildings serving as flexible energy units within greater balancing regions [8]. The essential role of transparent but still secure digital communications between flexible energy units was one focal point of the project Flex4Energy, which develops an open platform for regional energy markets [9]. The district envisioned in the SWIVT project would find here its ideal application.

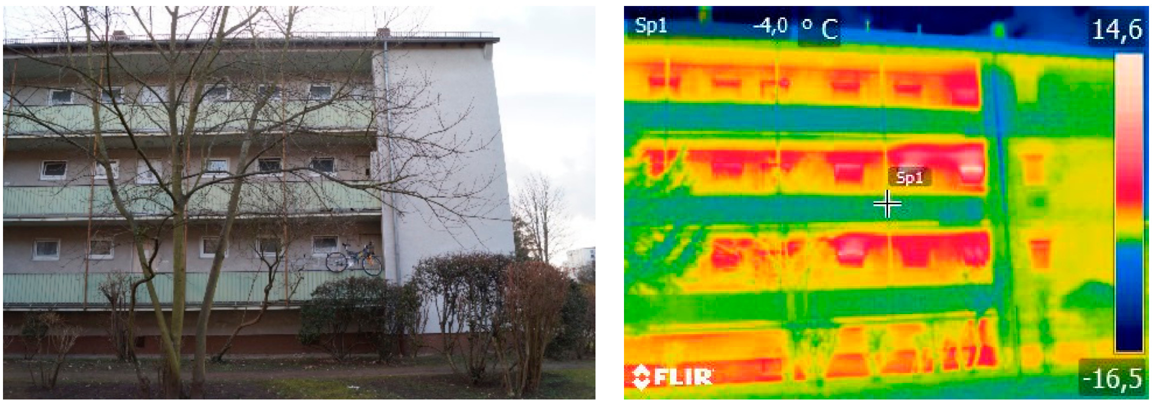
This paper presents the approach to building renovation developed within the SWIVT concept. Interdependent parameters between renovation measures, the addition of new, energy-efficient living area, and different thermal and electrical systems on district scale are explored through three scenarios—High-Exergy, Mid-Exergy, and Low-Exergy—developed for an existing residential area in Darmstadt, Germany. Findings support the implementation of an energy system on district scale as a more resource-efficient solution for building renovations than the improvement of the thermal envelope of individual buildings. The primary energy balance of existing residential areas can be improved by more than 30% compared to a standard renovation through minimal intervention measures on the existing building stock, thanks to an efficient energy supply system on district scale and the connection of its components within an operational strategy.

2. Documentation of Current Building Stock on Project Site Moltkestraße 3 to 19 in Darmstadt

The project site is located in the district Bessungen in Darmstadt and consists of five multifamily social housing buildings property of the consortium Bauverein AG, with a total living floor area of 3.630 m^2 on a 10.453 m^2 plot. The northeast to southwest oriented linear apartment blocks were built in the years 1949–1952 and consist of two- to three-floor-high lightweight concrete constructions with saddle roofs and cellars. The small residential district has a total of 87 apartments with an average of 23.4 m^2 per resident. The lot is suitable for densification measures and for the introduction of new communal functions in the currently underused green areas between the buildings [10]. The original plans divide the buildings in three categories: Ledigenheim I and II (literal translation: home for unmarried), Types E/F, and Type P. Ledigenheim I and II (LI and LII) consist of 1-person apartments accessed through an open gallery on the northeast side. The two twin constructions of Types E/F consist of 2–3-person apartments spanning the whole width of the construction and connected vertically through three stairwells per building. Both categories have small southwest balconies. Type P consists of a 2-floor construction with four 3-person apartments and no balconies, with a northwest to southeast orientation. This categorization is clearly recognizable in the floorplans of the buildings, shown on site in Figure 2.

Figure 2. Floorplans of Moltkestraße 3 to 19. Areas marked in red are suitable for extensions.

The buildings are not renovated except for a window replacement in the 1980s and the application of roof insulation where the living area was extended to the attic floor, which is the case for two apartments per block in buildings of Types E/F. The building envelope presents poor thermal quality, leakage, and condensation problems. Ceilings, staircases and outer doors are insufficiently acoustically insulated and necessitate fire-proofing measures, while apartments lack barrier-free access. Deficiencies of the façade were determined through a detailed inspection with an infrared camera performed at 5 a.m. on 4 February 2015. Strong losses through the outer walls were observed together with thermal bridges, especially pronounced along the balconies, the window lintels, and the cellar floor. While helping with the analysis of site-specific deficiencies, these images, shown in Figure 3a,b, show a typical picture of the conditions of the non-renovated building stock from the 1950s to the 1960s.



(**a**) (**b**)

Figure 3. (**a**) East façade of Moltkestraße 19. (**b**) Infrared picture of the east façade of Moltkestraße 19.

Thermal energy is supplied through a floor gas heating system. LI and LII have significantly higher gas consumption. LII supplies LI through two constant temperature boilers located in the cellar. The pipes are in good condition and largely insulated, but the control is not efficient. Both boilers are always running together and working temperatures are fixed, so that high amounts of unnecessary heat is produced. The heat-delivering elements are large-volume radiators with manual control valves.

Type P's high heating demand can be justified by a larger surface area to its volume. Figure 4 shows the energy consumption for the five buildings according to the evaluation of project partners ENTEGA AG (Darmstadt, Germany) the energy provider, and of Bauverein AG, (Darmstadt, Germany) the housing company. The district's energy demand balanced on net floor area is 211 kWh/m^2 for heating and warm water, which corresponds to the typical consumption for buildings of the same typology and location based on EN ISO 15316 [11] and 49 kWh/m^2 for power demand.

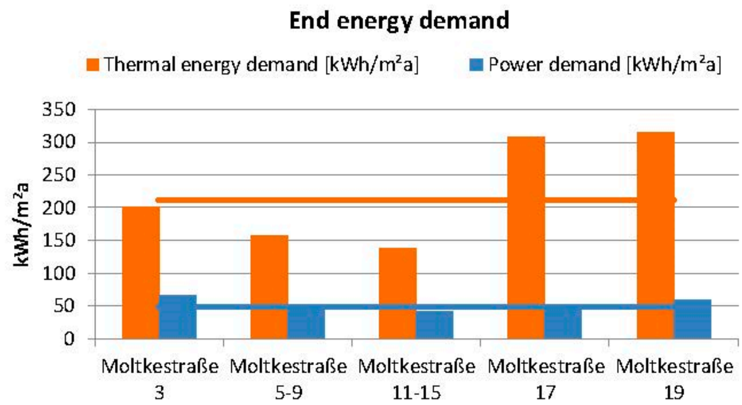


Figure 4. End energy demand of the buildings Moltkestraße 3 to 19. The horizontal lines represent the balance for the whole district.

3. Setup and Nature of the Study

SWIVT develops its specific approach to integral planning through a design methodology based on scenarios consisting of four modules: energy load, energy generation, energy conversion, and energy storage. Involved stakeholders agree on the requirements for each module at the start of the concept phase, taking into account mutually influencing parameters in order to create different design scenarios. This enables disciplines to develop specific approaches and solutions, while collaborating to the same overall goals. Three design scenarios were developed: High-Exergy (S1), Mid-Exergy (S2), and Low-Exergy (S3). These are evaluated against two reference scenarios: current stock (R1) and standard renovation (R2). Energy demand in R1 and R2 are benchmarked on measured data provided by ENTEGA AG. R2 represents the renovation of four buildings in Moltkestraße 27–37 performed in 2009, which achieves a total primary energy balance of 56 kWh/m^2·a [12]. Each design scenario should reach a 30% lower energy balance than the traditional renovation approach benchmarked by R2. An optimized implementation scenario, which will be built on site in the follow-up pilot project SWIVT II, projected to start in 2018, will be designed based on the results collected through the evaluation of the three design scenarios. The five scenarios and the requirements set within the modules are shown in Table 1.

The parametric study presented in the manuscript is carried out within a mathematical model developed in Microsoft Excel. The model integrates parameters from the building concept with parameters from the energy concept to show how different thermal loads for the renovated surface affect primary energy need on a district level. Within the model, it is possible to evaluate the interaction between differently renovated and new, energy-efficient living areas. Selected variables are the extension of each type of area and the final thermal load for the renovated portion, while the thermal load per square meter of new living area is kept constant. The next step will be a modeling study with the software Hottgenroth Energieberater 18599. The study will evaluate the necessary building refurbishment measures to meet thermal loads for each type of renovated living area according to the implementation scenarios. The overall aim is to prove a more efficient strategy for investing economic and ecological resources through minimal renovation and the use of renewable generated energy on site, against a standard renovation concept based on façade insulation.

Table 1. Requirements for different modules of design scenarios S1, S2, and S3, as well as for reference scenarios R1 and R2.

Scenarios [1]		Energy Demand [2]		Energy Generation [3]		Energy Conversion			Energy Storage	
		Heat	Power	Solar Thermal	Photovoltalcs	Gas Based	Gas/El. Based	Electricity Based	Thermal	Electrical
R1	Current stock	100%	100%	-	-	Boiler	-	-	-	-
S1	High-Exergy	70%	90%	75%	25%	Aux. Boiler	CHP [4]	-	hybrid TESS [6]	hybrid ESS [7]
S2	Mid-Exergy	60%	90%	50%	50%	Aux. Boiler	CHP [4]	HP [5]	hybrid TESS [6]	hybrid ESS [7]
S3	Low-Exergy	50%	90%	50%	50%	Aux. Boiler	-	HP [5]	hybrid TESS [6]	hybrid ESS [7]
R2	Standard renovation	40%	80%	-	-	Aux. Boiler	CHP [4] each building	-	-	-

[1] R = Reference, S = Scenario; [2] As a share of residual energy demand; [3] As a share of energy generating surface; [4] Combined Heat and Power; [5] Hear Pump; [6] Thermal Energy Storage System; [7] Electricity Storage System.

4. Building Concepts

4.1. Building Renovation

The energy loads of the buildings on site are compiled and balanced on total square meters of net living area on a district level. Targeted values for the residual thermal energy demand of renovated buildings are set at 70%, 60%, and 50% of current, while values for electrical energy demand are set at 90% of current. Yearly thermal energy demand for the renovated living area needs to decrease from 211 kWh/m^2 to 148 kWh/m^2 in S1, 127 kWh/m^2 in S2, and 105 kWh/m^2 in S3. In order to create different load profiles, two renovation concepts were designed: minimal and standard. The minimal renovation concept consists in the insulation of cellar ceilings and the replacement of windows and doors. Because of the strong temperature difference between the colder surface of the existing wall and the warmer surface of the new windows, these require a ventilation system in order to avoid condensation problems. The standard concept consists in the minimal concept with the addition of façade insulation and, where no additional floors are built, roof insulation. In this concept, new windows do not need an in-built ventilation system, because a lower temperature difference between insulated wall and glass panes will prevent cold bridges and thus the formation of condensation. All renovated buildings are provided with new balconies and/or terraces, replacing the old ones through detached structures to prevent cold bridges. Some balconies and terraces can be designed as winter gardens for passive solar gains and in order to introduce a distinctive architectural feature to the district.

The main cause of thermal energy loss at a district level is the thermal bridge created by the open gallery of buildings LI and LII. It is therefore decided to extend the living area to include the gallery and close the façade with a new outer wall. Due to normative regulation, an extension of the living area can only be approved if new walls comply with the minimum U-Value requirements [9], thus preventing the application of innovative architectural solutions, such as a winter garden, whose energy performance balances out on a system level but not on a component level. Since the two larger buildings on site require façade insulation the standard renovation concept is applied to them in all three scenarios. Since Building Type P is balanced as a new construction, only buildings of Types E/F are eligible to be modeled according to the minimal concept.

4.2. District Consolidation

Due to explicit requirements of the project partner Bauverein AG, the housing company, the renovation concepts are to be combined with the structural consolidation of the district through the creation of a new living area. This was benchmarked on R2, where net floor area increased by 87% through additional floors on top of existing buildings [12]. A new building in place of Moltkestraße 3, with a net living area of 550 m^2 on four floors, was modeled with the software IDA-ICE in order to create an estimate benchmark of the energy load of the new living areas. The building is optimized for passive energy conservation through a compact shape and a lightweight construction with high heat storage capacity thanks to wooden-fiber insulation. The apartments' floorplans cross-span the building's short side in a north–south layout, and a roofed balcony on the south side avoids overheating by completely shielding the south façade from direct sunlight during the summer months. The façade's window-to-wall ratio (WWR) is 0.7 on the south side, 0.1 on the east and west sides, and 0.25 on the north side. The building energy simulation results are 34 kWh/m^2·a for thermal energy demand and 74 kWh/m^2·a for total electricity demand, out of which 10 kWh/m^2·a are allocated to auxiliary power for mechanical ventilation and for the operation of a heat pump. To render this approximation more fitting, all new volumes should present the same construction type and building services together with a comparable surface area-to-volume ratio and WWR.

The densification of the living area on site was discussed in an interview with the local department for urban planning. According to the current energy savings normative, both buildings of Types E/F can be extended on the southeast side up to the sidewalk, while Type E can additionally be extended on the northwest side [10]. Vertical densification can be implemented in order to consolidate the neighborhood without changing the quality of the green spaces, thus preserving an essential element of the existing district's identity. Digital models of the sun path on site have shown that the addition of up to two floors does not impact the amount of sunlight received by neighboring buildings. Horizontal and vertical densification is thus implemented in different combinations to create six building typologies, shown in Figure 5: A-1 and A-2 for Li and LII; B-1a, B-1b, B-2, and B-3 for Types E/F. B-2 introduces townhouses through the demolition of the vertical stairwells of Types E/F, while B-3 is a student residence complex with large common areas built by joining the twin constructions around a shared courtyard. Since neither extending the living area nor building additional floors are feasible options for Type P, the construction is eligible to be demolished and completely rebuilt [13] (p. 14). The resulting seven building typologies are shown in Figure 5.

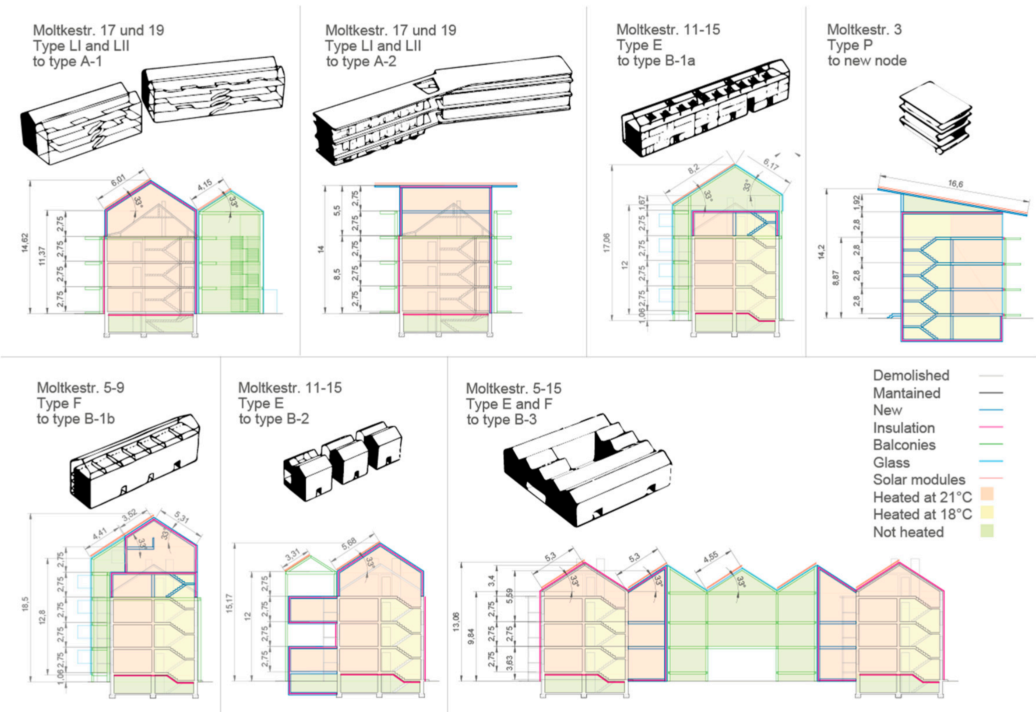


Figure 5. Seven building typologies for the densification of Moltkestraße 3 to 19 through the new living area.

5. Energy System Concepts

5.1. Energy Generation

Heat is generated at about 60–70 °C through a Combined Heat and Power unit (CHP) in S1 and at 28–44 °C through heat pumps in S3, while S2 is equipped with both a CHP unit and heat pumps. While all scenarios are equipped with an auxiliary high-efficiency boiler and can supply heat at different temperatures by means of mixing water or through a cascading system, building renovation concepts are assigned to scenarios according to the operating temperature of the main system in order to minimize energy losses. In S1, Buildings E/F are renovated according to the minimal concept, thus not insulated. In S2, one of the two twin constructions is renovated according to the minimal concept, while the second building is converted into townhouses and renovated according to the standard concept. In S3, low-temperature heating requires a higher thermal quality for the building envelope, so the standard concept is applied to all buildings on site. Resulting scenarios are shown in Figure 6, while Table 2 shows net floor areas for the scenarios divided into renovated and new. Renovated net living areas do not match existing floor areas due to conversion measures and other building interventions.

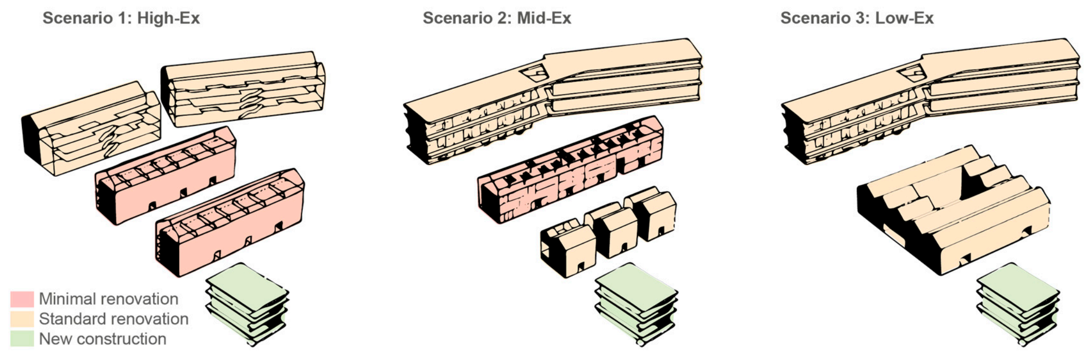


Figure 6. Building types and renovation concepts grouped by scenario.

Table 2. Net floor areas for the three scenarios divided into renovated and new.

Net Living Area in m²				
Scenario	**Renovated Living Area**	**New Living Area**	**Total Living Area**	**% Increase**
R1	/	/	3.630	0%
S1	3.771	3.033	6.804	87%
S2	3.152	3.833	6.984	92%
S3	3.609	2.577	6.794	87%
R2	2.242	1.960	4.206	88%

Resulting energy demand for each scenario is shown as district load in Figure 7a and balanced on m^2 net living area in Figure 7b. Total energy demand on the district level in the three scenarios is respectively 112%, 104%, and 92% of the current demand, while specific energy demand per m^2 floor area is respectively 60%, 54%, and 49% of the current demand.

Renewable energy is generated through photovoltaic modules and solar thermal panels covering 250 m^2 and 750 m^2 of roof area respectively in S1, and 500 m^2 each in S2 and S3. Due to collecting surfaces with different orientations, a district approach profits from continuous energy generation throughout the day. Table 3 shows energy generation through roof panels on site according to the requirements set in the respective modules for the scenarios. Due to the hybrid thermal and electrical energy storage systems steered by the SWIVT-Controller described in the following paragraph, the share of generated heat and power used on site, comprised of direct and delayed use, is close to

90% for power and 100% for thermal energy. This allows a high share of total energy consumption to be covered by renewable energy generation through roof collectors despite unfavorable volumetric ratios of roof to living area.

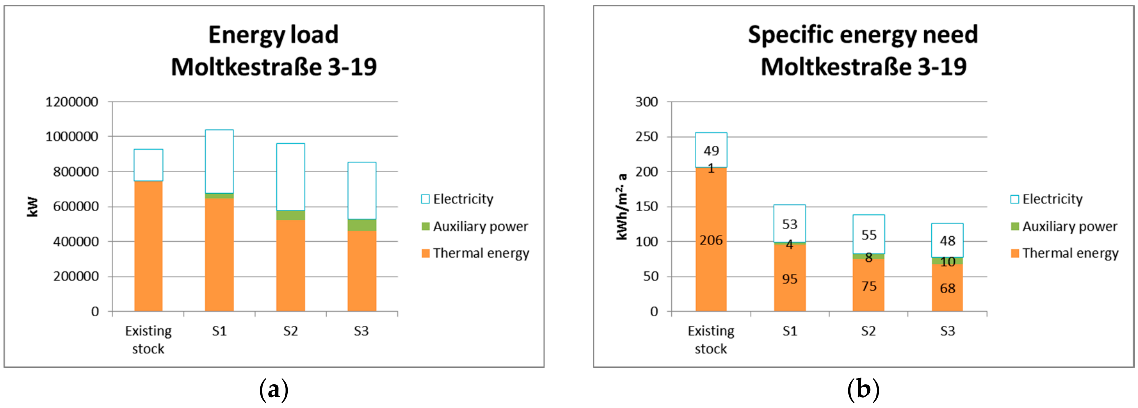


Figure 7. Energy demand for each scenario as district load (**a**); and balanced on m^2 net living area (**b**).

Table 3. Energy generation by scenario and type of collector.

Renewable Energy Generation in kW·a				
Scenario	**Solar Thermal Panels**	**% of Thermal Energy Need Covered**	**Photovoltaic Panels**	**% of Power Consumption Covered**
S1	487.500	75%	37.500	9%
S2	325.000	62%	75.000	16%
S3	325.000	71%	75.000	18%

5.2. Energy Storage Concepts

All scenarios are equipped with a hybrid thermal and electrical system that can store and distribute energy between the buildings. The requirement "hybrid" describes a system able to store energy for different time spans and with different reaction speeds. On the thermal side, it also implies storing heat at different temperatures. This is achieved through a system of heat-cascading fluid storage in the form of concrete tanks filled with a mix of water–glycol, with in some cases the addition of paraffin wax, a phase changing material (PCM). The PCM-system has a reaction time of 2–2.5 h due to a heat transfer coefficient of 0.2 W/(m^{2}K) and melts at 28–30 °C, while the water–glycol system releases heat at 0.58 W/(m^{2}K). The thermal strategy deployed through the SWIVT-Controller aims at exploiting these characteristics to minimize heat losses from the solar thermal collectors and the operation of the CHP unit through an algorithm based on predictive control. On the electric side, a system combining lithium-ion batteries with a flywheel aims at minimizing power losses from the photovoltaic collectors and the co-generated power from the CHP unit through dynamic power distribution. The base load is stored in batteries with a combined energy content of 140–200 kWh, while peak loads are stored in a flywheel with an energy content of 8–10 kWh. The electrical strategy deployed through the SWIVT-Controller aims on the one hand at optimizing the use of the battery in order to prolong its life, and on the other hand at an economically ideal operation through an intelligent operating algorithm able to forecast energy flows and power market prices.

Primary energy demand is calculated for heating, warm water, and auxiliary power according to DIN 18599 and DIN 4108-6. In S1 and S2, the CHP unit covers half of the residual thermal load and generates electricity as a by-product at a 50/50 ratio. In S1, an auxiliary heater (boiler) covers the residual thermal load, while in S2 this is shared between heat pumps and an auxiliary heater. In S3, heat pumps cover half of the thermal load of the district, and a boiler covers the remaining load.

Figure 8a shows the distribution of energy sources to cover the energy need of the district in the three scenarios. Assuming a primary energy factor (PEF) for natural gas of 1.24 and a PEF for grid power of 2.4 yearly, the primary energy need for the three scenarios is evaluated at 28 kWh/m^2, 25 kWh/m^2, and 35 kWh/m^2, respectively, as shown in Figure 8b. All three scenarios reach at least 30% lower balances than R2, which has a primary energy need of 55.7 kWh/m^2.

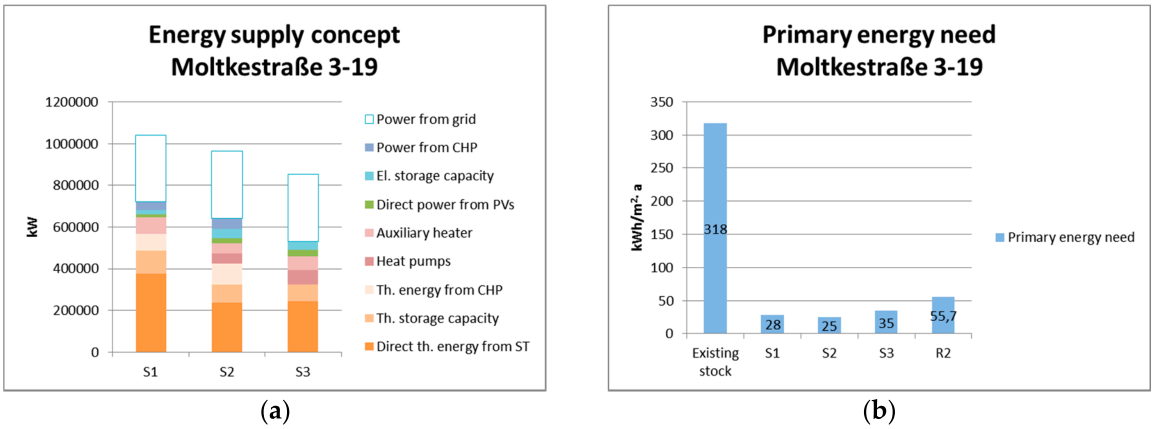


Figure 8. Energy supply concept for the three design scenarios (**a**) and comparative evaluation of the primary energy need for reference scenarios and design scenarios (**b**).

6. Results

Results are interpreted as follows:

(1) The design of an energy system on a district scale, while allowing higher residual thermal loads from individually renovated buildings compared to a standard renovation, reaches 91%, 92%, and 87% lower primary energy balance than the existing stock.

(2) Replacing requirements for the design of building renovations based on minimal U-Values for single components with one based on a system-scaled primary energy balance would allow the implementation of original architectural design solutions.

(3) In order to succeed, this concept requires an operational strategy able to deliver the required performance from each energy supplying, converting, and storing component. This operational strategy is largely in place in the SWIVT project, and should be validated on site in the follow-up pilot project, SWIVT II.

(4) Furthermore, the concept requires a business model able to finance a profitable investment for all parties involved, and a contracting model able to clarify and define stakeholders' roles and obligations.

7. Discussion

- The need for less intervention could help investment in more qualitative assemblies. For example, organic insulation such as wood fiber or wool could be chosen over mineral and synthetic products.
- Local energy generation is an essential step towards climate protection goals [1]. The results presented in this paper suggest that coupling technologies for energy generation, storage, and distribution on a district level has a higher impact on lowering the primary energy need compared with the renovation measures for building envelopes. Whether this is a more resource-efficient solution with respect to costs and environmental impact, for example, by taking greenhouse gas emissions during manufacturing into consideration, needs to be validated. There is, however, evidence that this is already the case for photovoltaics [14].

- Different models for selling locally generated heat and power to tenants are currently employable in Germany [15]. However, the profit margin is not sufficient to finance a broader investment, neither in complex or innovative technologies nor on a wider scale. This is partially due to the current regulatory framework ("Erneuerbare Energie Gesetz", in short EEG), which states that locally generated power is not freed from the levy on renewables, whenever it is not directly consumed by the owner of the installation. Locally generated power stored for later use, for example in batteries, is also subject to the levy [16]. The German parliament voted to change this levy in the amendment to the EEG 2016, which comes into effect in 2017 [17].
- Future energy prices and the introduction of a carbon tax have a crucial impact on the design of the operational strategy, thus altering the life-cycle cost analysis and hence the financial model for the concept. Close collaboration between policy makers and the industry is required in order to work towards aligned goals.
- A further open question is tenants' willingness to subscribe to the proposed contract. Even though users can be incentivized by the quantifiable financial advantages and low environmental impact of a high share of locally generated energy, the profit margin of the system will not be available if a determined share of local users opts out. Therefore, it is essential to involve the user in the discussion of a feasible business model.

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