Integration of decentralized energy systems in neighbourhoods using the energy hub approach

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Keywords: energy hub, renewables, energy scenarios, urban energy system, neighbourhood

Abstract

This paper describes a method of integrating decentralized energy systems at neighbourhood scale. The method is based on the energy hub concept, which describes and manages the relation between input and output energy flows and thus can be used to optimize energy consumption. The original energy hub concept is further developed to include decentralized and local energy technologies such as photovoltaics, biomass, or small hydro power, together with district heating systems, building and district conversion and storage technologies at neighbourhood level. Additionally, input from a building simulation tool for evaluating time-dependent buildings energy demand is included in the method. The proposed approach can be used to evaluate and size urban energy systems according to their energy-autonomy, economic and ecological performance. The advantage is that the energy supply systems and local energy storage systems can be evaluated in a combined way at district scale. The suggested method allows to lower peaks in energy demands of neighbourhoods on the electrical grid and to reduce the overall consumption. The developed method is finally applied on a case study for which future energy scenarios of different implementation scale are suggested. The area is located in a village in the mountains and contains 29 buildings. Suggested scenarios include decentralized and local renewable energy sources and district and small

31 heating networks. Results show a variation of 52 to 98 tons of CO₂ emissions, and an
32 energy autonomy between 64 and 92%. In case of CO₂ emissions, the best solution is
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1. Introduction

European countries are promoting the use of renewable energy sources as an important measure to the reduction of the dependence on foreign energy imports, and in meeting targets to reduce the increase of global warming. For the case of Switzerland, an energy strategy is developed which envisions to decrease the current energy consumption

and that a major share of the future energy demand will be covered by hydro power and decentralized energy systems (DES) such as photovoltaics (PV), geothermal heat, wind energy converters, and biomass driven combined heat and power (CHP) [1]. A reliable integration of DES is a challenging task, and requires an update of the current energy systems. Renewables are typically integrated at building level and account for a small fraction of required energy. To increase the reliability of renewable and sustainable energy systems, current trends are towards integration of smart grid technologies and demand side management with the goal to use the available energy more efficiently. Thereby peaks in electricity demand can be shifted to periods where energy from intermittent renewable sources is available [2, 3]. The idea of an energy hub is building on that concept, by extending controlling demand and supply from electricity to multiple energy sources. It is a combination of multiple conversion, distribution, and storage technologies which are controlled in order to supply various consumers of energy. Thereby consumers can be a single large building complex but also a city quarter, neighbourhood, city, region, or even a country. An energy hub at district scale focuses on urban energy systems, where building integrated renewables such as photovoltaics, solar thermal collectors, hybrid collectors, or wind turbines can be combined with local and regional scale distribution technologies such as smart grids, micro-grids, district heating and cooling networks. The design of such multi-energy systems is not a simple task and requires computational methods which take multiple energy sources and technologies into account, and allows for optimization of the energy flows within the neighbourhood.

Tools to address the design and optimization of multi-energy system are addressed e.g. in [4-7], but the methods are typically applied at regional or even country level to integrate DES or other conversion or storage technologies. In these studies the integration of energy technologies at building level are not considered. However, for the optimal use

of environmental heat dependent technologies such as ground or air source heat pumps, it is important to take into account the energy performance of buildings and the interaction with such heat supply systems. But so far, methods which integrate local and decentralized energy technologies and the energy performance of buildings can rarely be found. Approaches, where mathematical programming techniques are used to optimize energy systems at neighbourhood level are for example a study which assesses challenges to the electrical grid if zero-energy buildings are integrated [8], or the assessment of economic optimal DES for an eco-campus in Japan [9] and optimizing the operation [10]. Mehleri et al. [11], reports on a mathematical model to size decentralized energy generation systems including a district heating network. In their modelling approach specific time periods are selected to size the energy systems. Similarly, a mixed integer linear program model that incorporates both demand side and centralized supply technologies is documented in [12, 13]. Another research effort which contributes to this topical area is the Distributed Energy Network Optimisation (DENO) model [14] which allows to select the optimal set of energy generation devices. In this case a finer time resolution is deployed, but the overall simulation period is limited to specific design days.

Another modelling tool which is designed to couple various energy systems and manage energy flows through regulating conversion, storage, and distribution of energy is based on the energy hub concept [15, 16]. This tool was developed to find the optimal dispatch of multi-energy streams in an energy hub. The energy hub modelling tool is based on optimization techniques, such as linear or non-linear programming, and can be used, to evaluate optimal design layouts of energy hubs, but also for operation or control of existing energy hubs.

First modelling examples of energy hubs address generic examples of simple hub layouts where energy sources such as natural gas and electricity are integrated [15, 16,

17]. Thereby all different conversion and storage technologies, which are present in the energy hub, are integrated in a single building and the hub supplies electricity, heat and cold at the output port. Examples which address real case studies are for example an energy hub in Baden Dättwil, Switzerland [18, 19] or in Waterloo, Canada [20]. The integrated technologies are typically based on local (centralized) energy technologies, such as gas, electricity, hydrogen etc. Energy hubs at urban scale are rarely addressed in literature. Nazar et al. [21] used the energy hub approach to optimize an urban electricity distribution system for investment, operational costs, and availability. La Scala et al. [22] address 24 multi-energy hubs which are connected with an electricity and a gas network. The combination of the energy hub concept and renewable energy integration at building level is to date limited to supply from local energy sources such as wood or biogas [18] or wind turbines [23]. The evaluation of building integrated conversion technologies, such as heat pumps or boilers while optimizing locally available renewable energy sources within a neighbourhood has not been addressed so far.

For existing energy hub configuration the model of an energy hub can be used for optimizing the operation of the hub configurations including electricity and gas networks. In this case input data on available energy potentials, and the required energy demand is not based on system design data, but the current situation and future projections of energy demand and sources. Examples in literature include the control of combined electricity and natural gas systems using model predictive control [24, 25], or a receding-horizon model-predictive controller for electric transmission systems with energy storage and renewables [26].

2. Problem definition

In the future the renewable energy share has to be vastly increased. Our energy systems will not rely on a single technology, but incorporate multiple energy sources. The

successful integration of multiple DES is dependent on the energy performance of individual buildings, and can only be optimally used, if technologies for conversion, storage, and distribution are taken into consideration during planning of the system. Furthermore, the reduction of the current energy consumption due to retrofitting of existing buildings is an essential step for successfully integrating DES. Available tools typically focus on one parameter but don't consider all together. Moreover, available methods usually don't assess the energy performance over the period of a year, which is essential to incorporate storage technologies, to decrease the use of energy imports from outside, and reduce the carbon foot print of the neighbourhood.

3. Proposed approach

This paper deploys the energy hub concept at urban level, considering the integration of DES at building and neighbourhood scale. As urban energy hub we understand not a single entity containing all necessary systems for transformation, conversion, and storing of energy, but that individual energy consumers and producers are spatially distributed over an area, which is relevant especially in case of transferring heat with the energy hub. This allows to take variable loads, systems, and energy sources of multiple buildings into account. The advantage of extending boundaries to the urban scale is that typically, multiple energy sources are available, which allows for a higher flexibility of the system. An urban energy hub is defined as a delimited system, which balances energy flows within the boundaries, but can be also connected to the local energy grid to extract or supply energy. Individual hubs can be connected and exchange energy flows with various types of distribution grids, such as electricity, gas or heat networks. To formulate the mathematical model of an energy hub at urban level, the original energy hub concept [15, 16] is further developed to represent energy systems, demand and supplies which are not just integrated within a single building but spread over a neighbourhood (see Figure

1). Building and urban energy systems for distribution, conversion, and storage of electricity and heat are integrated within the energy hub concept. Energy flows from various types of energy sources act as input information into the hub model (left part in Figure 1). Energy sources include DES integrated at building level (e.g. from distributed PV panels) or locally connected to a neighbourhood such as small hydro power plants or a CHP unit. Additionally the electrical grid can also supply electricity to the energy hub. Furthermore, the energy hub model uses information from building energy performance models on the hourly energy loads of the buildings (right part in Figure 1) within the neighbourhood. The mathematical model of an energy hub is combined with optimization techniques, and balances energy supply and demand within the system boundaries with different design objectives. The suggested tool allows to answer questions, such as the optimal combination of renewable energy sources to reduce carbon emissions, the optimal retrofitting of existing buildings and their systems within a neighbourhood, the optimal configuration of local storage units to increase energy autonomy of the neighbourhood, and to curtail peaks in energy demand in the low-voltage grid. Within this paper the energy hub concept is used in the design stage of DES and energy systems. However, with the integration of smart grids, smart meters, and multiple energy streams the tool of an energy hub can also be used to develop and implement control strategies for balancing supply and demand within a neighbourhood. The following section presents the modeling concept together with the mathematical representation and the integrated technologies. Section 5 reports on the application of the concept to a case study by defining and evaluating different future energy scenarios for a neighborhood and their evaluation regarding CO₂ emissions, potential towards energy autonomy, and reduction on the impact of the grid.

Figure 1. Concept of model components to integrate decentralized energy technologies at neighborhood scale.

4. Model description

The integration of DES at neighborhood scale depends on the energy demand of the neighborhood, the available potential for energy supply from different energy sources and the matching of energy demand and renewable supply. The method requires a three step approach: (1) estimation of demand, (2) estimation of renewable potential, (3) matching of demand and supply. Figure 2 shows the three steps in a flow-chart, and the following sections describe the steps more in detail. The first step requires the calculation of the time-resolved energy demand of buildings located within the hub boundaries. A building energy simulation model (BES) is deployed to calculate energy demand of buildings pertaining to heating and cooling. Furthermore electricity demand of buildings is calculated or taken from electrical meters. In addition to the energy demand, models which evaluate the time-resolved availability of energy from decentralized and local

technologies is evaluated as a second step. Decentralized energy can for example be provided by building integrated PV panels, solar thermal collectors or waste heat from individual buildings. Local (centralized) potentials account for energy sources which are not directly connected to a building but can be distributed over the whole neighborhood by plants using biogas or waste wood. Finally, the energy hub model is used to manage the energy flows of demand and supply. The energy hub model can include various energy technologies for conversion, transformation, and storage of electricity and heat. These technologies can either be integrated at district scale or directly at building level. The energy hub concept additionally accounts for distribution losses of district networks such as district heating networks (DH) or low temperature networks (LT) as shown in Figure 1. The energy flows in terms of electricity, heat, gas, hydrogen or wood which are gained by the various decentralized and local sources act as input to the energy hub model (Figure 2). The energy demand of buildings act as a second input for the hub model. Finally, the energy hub model can be deployed to evaluate and optimize energy flows for various sets of design configurations.

Figure 2. Flow chart of the three step approach

4.1. Energy hub concept

The energy hub concept is used to evaluate and optimize the management of energy flows. It represents storage, conversion and distribution technologies to account for the optimal dispatch between multiple energy carriers (e.g. electricity to heat, natural gas to heat, thermal solar to hot water heating, hot water storage, etc.) in order to supply sufficient electricity, heat, cold, gases or fuels to end users. The advantage of the energy hub approach is that energy consumption, costs, emissions etc. can be optimized in relation to conversion, storage and distribution of energy. The key concept is the use of multiple input energy sources which can be converted by the hub to multiple outputs. The conversion can be made by a single device or by a combination of multiple devices [15, 16, 17]. The conversions between inputs and outputs are characterized by efficiencies which are defined in the conversion matrix (see equation 1). Three possibilities are considered: a connection without losses indicated by an efficiency of $c_{\alpha\beta}=1$, a conversion with losses, which is indicated with a factor $0 < c_{\alpha\beta} < 1$, and no coupling $c_{\alpha\beta} = 0$ which means that this conversion is not possible. Since one energy carrier might be converted into different forms of energy (e.g. electricity directly used, or converted to heat), dispatch factors have to be determined. The dispatch factors v_i define how much of each energy carrier flows into each converter. The sum of all dispatches $\sum v_i$ of a single energy input must be equal to 1. Thus the multiple inputs and multiple outputs of an energy hub can be described by the following equation:

$$\begin{bmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\omega \end{bmatrix} = \begin{bmatrix} c_{\alpha\alpha} & c_{\beta\alpha} & \cdots & c_{\omega\alpha} \\ c_{\alpha\beta} & c_{\beta\beta} & \cdots & c_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha\omega} & c_{\beta\omega} & \cdots & c_{\omega\omega} \end{bmatrix} \begin{bmatrix} P_\alpha \\ P_\beta \\ \vdots \\ P_\omega \end{bmatrix} \quad (1)$$

In this equation $[L_\alpha, L_\beta, \dots, L_\omega]^T$ denotes the hub-output vector, $[P_\alpha, P_\beta, \dots, P_\omega]^T$ the hub-input vector, and the c terms make up the converter coupling matrix, where $\alpha, \beta, \dots, \omega$ are the different energy carriers.

The energy hub concept can be applied at different levels of complexity. The basic model is used for the optimal dispatch from a single energy hub for multi-energy carriers, so the power flows through the hub are optimized for a single specific period. This can be done for peak energy demand or annual energy consumption. More advanced formulations, as used in the present work, consider transient time series of demands and supply capacities. This is necessary in order to integrate storage devices, and to assess the energy demand and energy supply potential of fluctuating power sources such as renewable technologies. The multi-period model representations evaluate the dispatch of multi-energy carriers for a number of time periods. This can be done in various ways, either by solving multiple time periods simultaneously or by solving hourly time periods iteratively after each other. The energy hub concept can be used for the design of an energy hub layout, the integration of renewable technologies or for optimizing the operation of an energy hub.

The optimization problem can be formulated as finding the optimal dispatch of energy from different sources to cover electricity and heating demands of all buildings within the neighbourhood. Various objectives can be formulated, either as single objectives as for example the optimal dispatch to minimize CO₂ emissions and life-cycle costs, or multi-objective formulations where both objectives are evaluated simultaneously.

In case of an environmental objective function, the environmental impact associated with the life-cycle CO₂ emissions from the consumption of different energy sources, including generation and conversion is minimized:

$$F = \sum_{\alpha} a_{\alpha} P_{\alpha} \quad (2)$$

where F denotes the objective function, a refers to the life cycle emission coefficient including emissions due to production of the energy conversion technology and fuel consumption during operation.

Literature refers to different optimization techniques which are used in combination with the energy hub approach. Techniques which are applied, depend typically on the constraints and the objective space. These include linear formulations, mixed-integer linear programming, or nonlinear formulations. A summary of various techniques is given in [27]. The described formulations are implemented in MATLAB. For solving optimization problems the Optimization toolbox is used.

The optimization problem of the present contribution is defined as a linear programming problem since all equality and inequality constraint have a linear relationship. The mathematical representation of the multi-time period problem can be expressed with the following set of equations:

$$\text{Minimize} \quad \sum_{t=1}^{N_t} F^t(x) \quad (3)$$

$$\text{subject to} \quad C \cdot x = L \quad (4)$$

$$A \cdot x \leq b \quad (5)$$

$$lb \leq x \leq ub \quad (6)$$

whereby F refers the objective function, x are the continuous optimization variables, C_{ij} denotes conversion coefficients, L^T denotes the Load output vector, A_{ij} describes the distribution of possible combinations of energy sources, such as PV can either be used for electricity or used by a heat pump to provide space heating. b , lb and ub refer to the inequality constraints to represent the limits given for individual energy carriers during one time period.

4.1.1. Conversion technologies

Within the energy hub model different technologies for providing electricity space heating and cooling are represented. Technologies can be either integrated at building level, or are represented as centralized technologies which are connected to individual consumers by an electricity grid or a heating network. Building integrated technologies for providing space heating are for example oil or gas boilers, wood stoves, ground source and air source heat pumps. Centralized conversion technologies are for example boilers or combined heat and power plants which are based on biogas or wood chips. Electricity can be provided by different energy sources such as small hydro power turbines, wind turbines, by a combined heat and power plant driven by biogas, or by the grid. Within the energy hub concept conversion technologies are represented through an efficiency value for converting energy from one carrier into another. Assumed values for a number of technologies are summarized in the following table.

Table 1. Summary of technologies together with conversion factors of different energy carriers [28]

Integration level of technology	Symbol	Conversion Value	Conversion	Element	Integration
Building level	c _{pV-e}	0.95	PV to electricity	Transformer	Building integrated
	c _{grid-h}	4	Electricity to heat	GSHP	Electricity grid
	c _{grid-h}	3	Electricity to heat	ASHP	Electricity grid
	c _{wood-h}	0.7	Wood to heat	Stove	Building integrated
	c _{oil-h}	0.8	Oil to heat	Boiler	Building integrated
District level	c _{grid-e}	0.95	Grid electricity to electricity	Transformer	Electricity grid
	c _{hyd-e}	0.95	Electricity from small hydro power to electricity	Transformer	Electricity grid
	c _{wc-h}	0.8	Wood chips to heat delivered by district heating network	Boiler plant	District heating network
	c _{wc-h/} c _{wc-e}	0.55/0.22	Wood chips to heat delivered by district heating network and electricity through the electricity grid	CHP	District heating network/ Electricity grid

4.1.2. District heating network modelling

When an energy hub is integrated in a single building, spatial variations between energy suppliers and energy consumers can be neglected. The issue with designing an energy hub at district level is that in addition to centralized technologies, decentralized energy supply technologies have to be considered, and the spatial variation of the different consumers has to be taken into account. For some technologies such as electrical grids this often can be neglected, but as soon as a district heating network is integrated, distribution losses have to be taken into account. This means that depending on the distance of the energy consumer from the boiler or CHP plant, a factor which represents heat losses to the ground from the piping network is taken into account. This value may vary from consumer to consumer. In order to account for distribution losses, the energy hub equation (equation 3) has to be extended with a distribution loss matrix D :

$$L = C \cdot D \cdot P \quad (7)$$

where $D_{ij}=1$ means a connection without losses such as building integrated or electricity grids, and $D_{ij} < 1$ accounts for distribution losses such as heat loss from pipes to the ground or pumping energy.

4.1.3. Storage technologies

Storage technologies, both short term storage such as batteries, or thermal seasonal storage can be integrated in to the energy hub concept. Important variables which describe the performance of storage technologies are charging and discharging coefficients, self-discharging rate, and available capacities. Additionally, a constraint is implemented, which defines that electricity from renewables which is not used within the same time period is forced into the storage. Hence storage is represented in the energy hub concept based on the following set of equations:

$$0 \leq Q_{STO}^t \leq CP_{STO} \quad (8)$$

$$0 \leq Q_{STO}^{t+1} \leq \gamma_{CH,STO} \cdot P_i^t \quad (9)$$

$$Q_{STO}^{t+1} \leq \gamma_{SDCH,STO} \cdot Q_{STO}^t \quad (10)$$

$$0 \leq P_i^{t+1} \leq \gamma_{DCH,STO} \cdot Q_{STO} \quad (11)$$

where Q_{STO} is the energy available in the storage , CP_{STO} is the capacity of the storage, $\gamma_{CH,STO}$, $\gamma_{DCH,STO}$, $\gamma_{SDCH,STO}$ is the charging, discharging and self-discharging coefficient, and P is the available energy.

4.1.4. Simulation periods

The basic energy hub model is used for the optimal dispatch of multi-energy carriers, so the power flows through the hub are optimized for a specific period [16]. This could be for peak energy demand or annual energy consumption. More advanced formulations can be applied transiently to time series representing demands and supply capacities. Transient time series are relevant if storage technologies are included in the energy system. The transient version of the energy hub concept can be applied at different time periods simultaneously e.g. a number of hours, a whole week, a whole month or even a year. However, due to computational constraints typically a full annual simulation is not feasible, dependent on the number of variables in the objective space and the complexity of the system. To address the complexity of seasonal storage an iterative process can be applied which iteratively solves a number of time steps simultaneously.

4.2. Local and decentralized energy potentials

Potential sources of energy act as input into the energy hub concept. These sources can be either integrated at building level such as photovoltaic and solar thermal collectors,

or as locally available centralized potentials such as the collection of biomass, waste wood or hydro power. Additionally, connections to electrical, heat, or gas grids can be taken into consideration. The determination of potentials of the technologies includes radiation models, geographical information systems, reduced order models, measurements and qualitative estimations. Energy potentials (both decentralized and local) act as hub-input vector into the energy hub concept formulation (Equation 1). The determined capacities for individual resources cannot be exceeded within a time-step and are defined as inequality constraints within the optimization problem:

$$P_i^t \leq CP_{pot} \quad (12)$$

where P_i is the energy available and CP_{pot} is the capacity of the available energy potential.

4.3. Energy demand of buildings

For the sufficient integration and management of renewable energy technologies, time-resolved information on the energy demand of buildings is essential. For existing neighbourhood configurations measured data can be used to generate demand profiles for the energy hub. However, this information is typically difficult to retrieve. At the design stage of an energy hub layout the heating demand of a neighbourhood can be calculated using building energy simulation models (BES). These models (e.g. Energy Plus, TRNSYS, etc.) allow calculation of heating demands for hourly time-steps. To calculate the energy demand for a number of buildings within a settlement, city energy simulations can be deployed. These models are similar to the building simulation models but typically use a more simplified building model representation [29, 30]. For performing building or city simulation runs a number of input data such as geometry, construction, and weather data of the specific location is required. Additionally, input information on internal gains such as occupancy, lighting, ventilation rates, equipment loads are required (Figure 2). Especially information on

occupancy behaviour bears a certain level of uncertainty in the design stage of energy systems. However uncertainties of input parameters can be accounted for, by testing sensitivities of energy hub configurations to certain input data. Similar to the heating demand electricity demand of the buildings for appliances and lighting as well as the domestic hot water demand has to be determined for hourly time steps. The hourly demand are represented in terms of the hub-output vector in Equation 1.

5. An example

To explore the potentials of the proposed method, the energy hub concept is applied on a neighbourhood within a village in Switzerland (more details on the village can be found here [31]). The goal is to find the optimal building system layout to reduce carbon emissions, to increase energy autonomy of the neighbourhood, and to curtail peaks in energy consumption on the local grid. The case study was selected, because it contains different building types and the option for integrating renewable energy sources. The area is composed of 29 buildings which are connected with a low-voltage electrical grid (Figure 3). In this area different building types can be found, building type A consists of 10 historically protected buildings, type B consists of 9 residential buildings from the period 1900-1945, type C consists of 7 buildings which were constructed between 1945 and 1980, and one relatively new building from the year 2000 (type D). Buildings are mainly heated by oil or direct electrical heating systems (current systems are shown in Figure 3). However, for the present study it was assumed that buildings are retrofitted to the present standard (by increasing wall insulation, and retrofitting windows), and that systems will be replaced by more sustainable solutions. From the 29 buildings in the neighbourhood, about 19 buildings have the potential for utilization of solar energy for electricity or thermal energy production.

Figure 3. Case study district with 4 building types of different age (A-D), including information on oil, electrical and renewable heating systems, and available solar potential

5.1. Energy potentials and building energy performance

Hourly profiles of buildings energy demand pertaining to space heating are calculated with the building simulation tool Energyplus [23, 24]. Buildings have been simulated first for the present situation, and additionally for the retrofitted case, assuming improvement of the building envelope. Heating demands of the retrofitted buildings are aggregated for the 4 different building types and are summarized in Figure 4. Electricity use for domestic hot water, use of lighting and appliances is summarized in Figure 5, whereby the graph shows the hourly profile for a day. Potentials of building integrated renewable energy sources such as photovoltaics, solar thermal collectors and local renewable potentials pertaining to small hydro power, wood pellets, and wood chips are summarized together with loads for heating and electricity in Table 2 and yearly profiles in Figure 6.

Figure 4. Total daily space heating demand for the four building types A-D for 365 days a year

Figure 5. Electricity demand due to appliances and lighting for the four building types A-D for a day

Figure 6. Local and decentralized potentials of energy from hydro power, solar thermal collectors for scenario 4 (st 4), photovoltaic for scenarios 1-3 (pv 1-3) and scenario 4 (pv 4), and wood.

Table 2. Summary of heating and electricity loads of retrofitted building types together with renewable potentials (in MWh) for the scenarios.

	Scenario	Typ A	Typ B	Typ C	Typ D	Total
heating load		203	162	72	24	545
electricity load		239	186	77	17	521
PV potential	1,2,3	21	133	63	16	235
PV potential	4	21	0	63	16	101
ST potential	4	0	355	0	0	355
wood chips and pellets	1,2,3,4					800
hydro power	2,4					1503

5.2. Set up of energy hub layouts

Based on the available potential of renewable energy sources different energy hub layouts are proposed which will be evaluated using the energy hub concept. The goal is to identify the best energy hub layout in order to reduce CO₂ emissions, peaks on the electrical grid and increase the energy autonomy. The first scenario uses energy from photovoltaics, together with wood pellets, and a connection to the electricity grid. Scenario 2 adds a small centralized hydro power turbine with a capacity of 1 MW. Scenario 3 includes the integration of a district heating network, which is fired by a CHP plant. Scenario 4 uses photovoltaic installations and solar thermal collectors and a small thermal grid which allows to use heat from building type A also in building type B. The configuration of the energy hub layouts are shown in Figure 7. Note that all scenarios are additionally evaluated using electrical storage in scenarios S1s to S4s. Electrical storage is modelled with a charging, discharging, and self-discharging efficiency of 0.9. The different conversion technologies which are integrated in the scenarios are summarized in table 3. For the case study CO₂ emissions were minimised using the objective function given in Equation (7). The coefficients a_{α} define the CO₂ emissions coefficients of the individual energy carriers (summarized in Table 3). The values represent life-cycle CO₂ emissions

436 per delivered energy to the building or zone within the buildings. CO₂ values for
437 individual system configurations are retrieved from the Ecoinvent database [32].
438

Figure 7. Scenarios of energy hub layouts S1 to S4 and S1s to S4s

442 Table 3. Conversion values and life cycle CO₂ emissions dependent on systems and
443 energy source [28].

Symbol	Conversion Value	Conversion	Element	Distribution Value	a _a [g CO ₂ /kWh]	Integration
c _{grid-e}	0.95	Grid electricity to electricity	Transformer	1	136	Electricity grid
c _{PV-e}	0.95	PV to electricity	Transformer	1	102	Building integrated
c _{hyd-e}	0.95	Electricity from small hydro power to electricity	Transformer	1	13.6	Electricity grid
c _{grid-h}	3	Electricity to heat	GSHP	1	175.4	Electricity grid
c _{PV-he}	3	PV to heat	GSHP	1	127.1	Building integrated
c _{hyd-h}	3	Electricity from small water turbines to heat	GSHP	1	56.4	Electricity grid
c _{wood-h}	0.7	Wood pellets to heat	Stove	1/0.85 ¹	49.9	Building integrated
c _{we-h}	0.55	Wood chips to heat delivered by district heating network	CHP-plant	0.85	37.1	District heating network
c _{we-e}	0.22	Wood chips to electricity	CHP-plant	1	37.1	Electricity grid
c _{STC-h}	0.6	STC to heat	STC	1	27.0	Building integrated
c _{oil-h}	0.8	oil to heat	Boiler	1	340.0	Building integrated

¹ 0.85 refers to Scenario 4, in which the distribution losses due to the small network are taken into consideration

444 5.3. Results and Discussion

445 Figure 8 shows optimized annual distribution of energy sources for the 4 building
446 types (in % of total) for scenarios S1 to S4 (without storage) and S1S to S4S (with
447 storage). The results show how much can be covered by renewables and which percentage
448 has to be covered by the grid. Figure 9 shows hourly distribution of energy sources over
449 the period of one year for heating and electricity demand for scenarios S1 to S4. Figure
450 10 shows (for a selected number of days) the hourly distribution of energy from energy
451 sources for scenarios S2, S3 (left) and S2s, S3s (right). Figure 11 depicts energy demand
452 of all buildings [kWh.m⁻².a⁻¹] and resulting CO₂ emissions for the scenarios, the existing
453 situation, and the retrofitted situation (update of the building envelope but originally
454 remaining building systems). Figure 12 shows weekly peaks of grid electricity for all

scenarios, the existing and retrofitted situation. Figure 13 summarizes total CO₂ emissions together with the percentage of energy autonomy, energy efficiency and electricity peaks of all 8 scenarios, the existing and retrofitted case.

Figure 8. Distribution of energy sources for the 4 different building types A-D and the total neighborhood for heating and electricity over the period of one year for all 8 scenarios.

In the first scenario the decentralized energy sources PV and wood pellets are integrated. Results show that PV installations can reduce the grid contribution by about 35%, about 20% of the PV potential remain unused due to the intermittence of the available solar

potential. The integration of a small hydro-power turbine (S2) improves the energy autonomy. However, the electricity grid has to overcome periods in winter when the hydro-power potential is low (S2 in Figure 9). The integration of a small district heating network which is connected to a CHP plant fired by wood chips (S3) supports additionally PV with electricity production in periods when PV potential is not available, hence it improves the energy autonomy (Figure 10). The advantage of the combination PV and electricity from CHP can be clearly seen on winter days, when the solar potential is relatively low, as in Figure 10 (S3 January) while comparing the first (low solar potential) and the second day (high solar potential). The integration of a small network where a heating system can be shared amongst two building types (S4) shows additionally a slight increase in energy autonomy. If additionally battery storage with a capacity of 1 MW is integrated the contribution of the grid can be decreased by about 2% to 3%. The mix of photovoltaic and electricity from the small hydro power plant, the small network, together with short-term electricity storages achieves in this case the highest energy autonomy (92%). Results further suggest that retrofitting of the buildings reduce required amount of energy significantly (Figure 11- shift to the left). The resulting CO₂ emissions are also lower – especially for buildings with oil heating systems. The change of energy systems reduces mainly CO₂ emissions, whereas the efficiency remains unchanged, except for buildings which change to heat-pump based supply. It can be also concluded that with retrofitting of the building envelope and energy system adaptation measures the variation of energy demand between buildings of a city quarter can be significantly reduced.

The evaluation of the total performance in terms of resulting CO₂ emissions shows a variation between 52 and 522 tons. The best solution is given with the integration of PV, STC and hydro based technologies which shows 46% lower emissions than for a scenario with only PV and biomass based systems (Figure 13).

488 Additionally an important factor is the electricity peak curtailment during high
489 demand periods. Peaks can be reduced (from 460 to 98 kW peak). The retrofitting of the
490 building envelope reduces the total energy consumption, and the related peaks especially
491 for buildings with direct electricity heating systems (Figure 12). Again a mix of multiple
492 sources, such as electricity from PV and a CHP unit can reduce these peaks which have
493 to be covered by the electrical grid, from 459 kW to 98 kW (Figure 12). Hence electrical
494 grid capacities can be sufficiently reduced if parts are covered locally. Options with only
495 PV and heat pump based heating systems stabilizes grid electricity peaks to around 100-
496 120 kW over the whole year. Hydro power further decreases peaks mainly during summer
497 time, where for a long time no electricity from the grid is required. The installation of a
498 CHP unit further reduces peaks during winter time, with the lowest peaks of 98 kW,
499 which results in a total reduction of 79 percent compared to the existing situation.
500 Electrical storage shows in this case a limited influence, only the combination of CHP
501 and PV shows some effect during winter time.

502

Figure 9. Weekly distribution of energy sources based on the optimization for emissions over one year for heating and electricity demand for scenarios S1 to S4. Electricity is provided by the grid (el-e), PV (PV-e), hydro (hy-e), CHP (dh-e), heating is provided by the grid (el-h), PV (PV-h), hydro (hy-h), wood (wo-h), district heating (dh-h), and solar thermal collectors (st-h).

Figure 10. Hourly distribution of energy sources based on the optimization for emissions over selected days in January (upper graphs) and July (lower graphs) for heating and electricity demand for scenarios S2, S2s, S3 and S3s.

Figure 11. Buildings annual resulting CO₂ emissions [tCO₂], energy consumption [MWh] for the present (pre) and retrofitted (ret) case, and the 8 scenarios.

Figure 12. Maximum energy (power) required from the grid within a week for all scenarios S1 to S4s together with present maximum value.

510

511

Figure 13. Efficiency of buildings [kWh.m⁻².a⁻¹], annual CO₂ emissions [tCO₂], peak on electrical grid [kW], and level of energy autonomy [%] for all scenarios and the present (pre) and retrofitted (ret) situation.

512

513 6. Conclusion

514 This paper presents a method of integrating energy from DES at district level
515 using the energy hub approach. The successful integration of energy from decentralized
516 intermittent sources depends heavily on the optimization of the energy systems. The

method of an energy hub applied at neighbourhood level has the advantage that not only the integration of technologies at building level but various technologies both decentralized and locally (centralized) can be taken into account, which allows, that energy can be shared amongst various consumers and producers. The model presented in this paper is a flexible system which allows to add various types of technologies for distribution, conversion and storage of energy which are present within a neighbourhood. The energy hub method as described here allows for evaluation of energy, economic, and environmental criteria. Typically the integration of renewable energy sources are not evaluated at neighborhood level, and not in a time-dependent resolution. However for the right balancing of demand and supply, the temporal availability has to be accounted for, in order to more efficiently revise the current energy system and meet the targets of future energy plans.

The case study shows the potential of this approach, by evaluating the contribution of the grid in comparison to more sustainable solutions, including the evaluation of resulting CO₂ emissions, energy efficiency, peaks in energy consumption and level of energy autonomy of the neighborhood. Results show for all scenarios a significant reduction of CO₂ emissions (between 81 and 90%), an increase of the energy efficiency (between 53 and 55%), an increase in energy autonomy (between 60 and 87%), and a curtailment of peaks on electrical grid (between 73 and 79%). Results show that the integration of certain renewable systems allow for more flexibility than other sources. However in all cases the grid is still required for electricity usage due to appliances. Although locally available energy sources would be sufficient to cover retrofitted energy demands, the energy autonomy of the neighborhood is limited to 86% (for non-storage scenarios) due to the mismatch in time of demand and supply. This is especially valid in winter periods when the solar contribution is low. Best performing scenarios in

terms of energy autonomy integrate a heterogenic mix of energy sources. Further improvement is limited without the integration of energy storage to overcome periods when intermittent energy sources are not available. For this specific case study the combination of retrofitting and the right system selection reduces electrical grid peaks to more than one fourth of the initial value.

The focus of this contribution lies on the re-design and sizing of the urban energy system. However the design of an adequate control approach for such a system is not a trivial task, taking the different levels of centralized technologies, building integrated technologies and energy demands into account. This is not accounted for in the present contribution, and bears an additional area of research which has to be explored in the future. Further limitation are given due to simplification of temperature levels for the district heating network to a fixed temperature, with the integration of low-temperature systems, where waste-heat at different temperature levels come into play, this simplification needs to be further explored.

7. Acknowledgement

The research presented in this paper is supported in part by funds from the CCEM IDEAS4cities project and the Swiss Competence Centres for Energy Research project “Future Energy Efficient Buildings and Districts”.

Nomenclature

A	distribution of combinations	ASHP	Air source heat pump
b	inequality constraint	BES	Building energy simulation
C	converter coupling matrix	CHP	combined heat and power
CP_{STO}	storage capacity [W]	CP_{POT}	energy potential [W]
D	distribution loss matrix	DH	district heating

567	-e	electricity	EL	electricity grid
568	F	Objective function	$\gamma_{CH,STO}$	charging coeff.
569	$\gamma_{DCH,STO}$	discharging coef.	$\gamma_{SDCH,STO}$	discharging coeff.
570	GSHP	ground source heat pumps	-h	heating
571	HY	hydro power	L	hub-output vector
572	lb	lower boundary	LT	Low temperature network
573	Q_{STO}	stored energy [kWh]	P	hub-input vector
574	PV	photovoltaic	ST	solar thermal collectors
575	STO	storage	t	time step
576	ub	upper boundary	v	dispatch factor
577	WO	wood chips/pellets	x	continuous optimization variables
578	$\alpha, \beta, \dots, \omega$	energy carrier		
579				

580 8. References

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