Abstract – This paper presents a hierarchical multiple-level model approach for the examination of the optimal power supply strategy for a larger (geographical) region, such as a city, or a county. The multiple-level model consists of hierarchically ordered parts of the region, forming the levels. The levels exchange energy. Variations on load demand or technology infrastructure of one part of the region affect other parts. The aim of this paper is to develop a methodology to analyze the optimal power supply of the region for different scenarios. Bottom-up optimization is proposed to allow the comparison of different power supply scenarios with respect to their costs. The use of decentralized (renewable) energy plants can be compared to the operation of centralized plants. The performance of small and large storages can be analyzed and differentiated. The cost optimal positioning of storages and conversion technologies and the optimal assignment of a new technology to a level can be studied. Also, the demand for centralized conventional power plants can be minimized using the multiple-level model. The examination and comparison of different supply scenarios allows to elaborate recommendations for action and investment for the analyzed region.

INTRODUCTION

In today’s energy infrastructure, the energy flows of different carriers such as gas or electricity are mostly considered to be independent. However, the integrated examination of various energy carriers generates synergy effects, as they occur e.g. in combined heat and power (CHP) plants. In addition to multiple energy carriers, a number of conversion technologies can be analyzed together. The aggregation introduces flexibility in the load supply, as increasing generation possibilities for each energy type increases the degree of freedom in the generation. Consequently, the simultaneous analysis of multiple energy carriers and a number of conversion technologies establishes degrees of freedom in the load supply, and enables its optimization.

The energy supply of larger regions, such as counties or cities, is carried out by a number of differently sized generation units. Decentralized small plants supply limited parts of the region, like houses or districts, while large centralized plants allocate the generated energy to a city or a community. However, the energy supply of e.g. a district is not independent, but depends on the energy production and consumption of e.g. the whole city, and vice versa. Generally speaking, changes in the production or the structure of one part of the region affect the whole region. This motivates the modeling and analysis of larger regions instead of focusing on a small area.

Especially, increases in distributed generation (DG) [1] affect the (multiple) power supply infrastructure of a larger region. E.g., if local authorities decide to build solar thermal collectors on the rooftops, less district heat will be demanded from e.g. the district’s Combined Heat and Power plant (CHP).

The aim of this paper is to examine the multi energy supply system of larger regions like communities, cities, or counties. Objectives are the determination of the optimal power supply strategy for the region, and the examination of the influences of distributed generation. Also, the optimal storage operation for various energy carriers in combination with intermittent generators such as photovoltaic or wind is of interest.

This paper proposes a multiple-level model approach to examine the region’s power supply. Multiple-level models are characterized by hierarchically ordered actors or groups of actors that interact by information exchange or goods/powder flow. The region is split up into its political units that build the levels. Each level “owns” a number of conversion technologies connected to the grids (electricity, gas, etc.). The levels exchange energy. Using the model, impacts of changes and effects of DG and storages on the optimal power supply can be analyzed. The multi energy and multiple conversion technology system is modeled with the energy hub concept of the Vision of Future Energy Networks Project (VoFEN) [2].

Multiple-level models apply in various research areas, such as control theory [3], the Petroleum Industry [4], and economics [5, 6]. In energy supply they have not extensively been studied. Ref. [7] models a two-level system consisting of an energy supplier and a household. The energy supplier maximizes its profit, taking into account that price decisions influence the household’s behavior. In [8], a methodology for the examination of energy infrastructures with a high penetration of decentralized technologies is presented. Consumers are modeled on different levels by aggregating several consumers to clusters. This allows the evaluation of the performance of distributed generation based systems regarding costs, emissions, etc.

In contrast to [7] and [8], the multiple-level model proposed in this paper permits the consideration of more than two levels, and levels are distinct in their conversion technologies, not only in the number of aggregated consumers. The model enables the examination of DG and storage use on different supply levels, its optimal placement...
for power supply, and its effects on other levels and their energy infrastructure.

In the literature, physical placement of DG and storages for e.g. minimizing losses [9, 10, 11], or increasing power quality [12, 13, 14] has received significant attention. Social aspects of DG use are examined in [15] and [16]. However, the examination of effects of DG and storages on different regional (supply) levels, and the optimal power supply strategy for a larger (geographical) region has not been addressed yet, to the best knowledge of the author.

The remainder of this paper is organized as follows: Sec. II gives the motivation for this work, and introduces the multiple-level model. Sec. III describes the application of the model using an example. Then, the optimization procedure is described (sec. IV), and the abilities of the multiple-level model are presented in sec. V. The paper closes with conclusions and future work (sec.VI).

MULTIPLE-LEVEL MODEL

The ability to use synergy effects motivates the simultaneous consideration of various energy carriers for future energy infrastructures [2]. These energy infrastructures are built of different (supply) levels. Centralized power plants and decentralized units supply the load demand.

Both production on different levels and multi energy considerations offer a certain degree of freedom in the supply of a region’s energy requirements. Energy can be produced centrally and then be distributed, or it can be generated close to the consumers. Also, demand can be supplied using any available and appropriate technology and energy carriers, e.g. heat can be produced either by a gas furnace or an electrical heating. Consequently, when considering a larger region, such as a county or a city, with different generation levels and multi energy carriers, the following question arises:

1. Which will be the optimal power supply strategy, given the objective function, the available technologies, and the load demand of the region?

The optimal power supply determines the operational policies of the region’s technologies that minimize a given objective function. The objective function includes e.g. costs, emissions, or social criteria.

Distributed generation and the use of renewable energy resources are likely to increase in the next decades [1]. They affect the energy networks [17], and influence the requested amount of conventionally produced energy. The time gap that often exists between generation and consumption caused by the intermittent nature of renewables can be bridged using energy storages. Consequently, emerging research areas for the energy supply of larger regions are:

2. In order to achieve optimality of the energy supply, do decentralized (renewable) power plants perform better than centralized units, with respect to the objective function? Or vice versa?

3. Do centralized and decentralized storages affect the system optimality differently? If yes, which kind of storage performs better?

4. To what extend will it be possible to reduce the number of centralized conventional power plants when renewable energies contribute more to energy production?

A multiple-level model of the multi energy supply of a larger (geographical) region is introduced in this paper that allows the examination of questions 1 to 4.

In the context of this paper, a “larger (geographical) region” denotes an area such as a county, a community, or a city, where different generation technologies supply different parts of the region. The multiple-level model consists of hierarchically ordered parts of the region. The (sub-) regions exchange energy. Variations on load demand or technology infrastructure of one part of the region affect other parts.

In the sequel, the construction of the multiple-level model is explained.

A. Levels

The multiple-level model structures the region of interest hierarchically using different levels. One possibility to select the levels are the distribution networks (e.g. 10kV/22kV,…, for electricity; <1bar,…, for gas,…). However, the networks of different energy carriers may not be overlapping perfectly. This prohibits a unique level distinction, because if a technology is connected to two (or more) energy carriers, there are two (or more) possibilities to assign it to a level. The same problem occurs when distinguishing the levels by the installed power. Consequently, technical criteria do not serve for the level distinction, as technologies processing several energy carriers can be assigned to different levels.

Thus, this paper proposes the level selection according to political units, like villages, counties, or districts. They are unique, straightforward, and comprehensible. Also, their hierarchy is predefined. Exemplarily, fig.1 depicts a possible political subdivision. It is not necessary that each political level is part of the multiple-level model. The levels have to be selected appropriately for the considered region, but if one modeling level is not of interest for the region, or simply is not present, it can be omitted.

![Fig. 1: Possible political division of a larger region](image-url)
B. Multiple Energy Carriers

In the multiple-level model, several energy carriers, like electricity, heat, or gas are considered simultaneously. Therefore, the energy hub concept developed within the VoFEN project of ETH Zurich [2, 18] is applied.

The energy hub is a unit that allows the conversion, conditioning and storage of multiple energy carriers. The hub (fig.2) consumes power $P$ at its inputs ports, and converts it to supply the load $L$ needed at the output ports. Locally available and renewable energies $R$ are also consumed by the hub. Power $T$ can be fed into the grid, and energy $E$ can be stored.

The hub is mathematically represented by a converter coupling matrix $C$, and a storage matrix $S$ [19]:

$$
(L + T) = \begin{bmatrix} C & S \end{bmatrix} \begin{bmatrix} (P + R) & E \end{bmatrix}^T
$$

(1)

At each time instant, the power balance has to be maintained: the sum of outputs $L$, $T$ has to equal the sum of the converted input powers $P$, $R$ and the power $E$ flowing into or out of the storages. The renewable power $R$ available at the hub input cannot be influenced, as its generation depends on external factors like wind or sun. Produced surplus energy can be fed into the grid, $T$. The power consumption of the hub, $L$, has to be supplied by renewable energies $R$ and conventional energies, $P$. The power $P$ has to be bought from (external) energy suppliers.

Each energy carrier is characterized by a number of different properties, like CO₂ emissions, costs, compensation for energetic recovery into the grid, etc. The aim is to determine the optimal power dispatch (OPD) for the hub with respect to the criteria of interest. Therefore, the objective function $f$ including all criteria of interest is minimized, establishing the optimal input power $P^*$ and the optimal storage operation $E^*$:

$$(P^*, E^*) = \arg \min f(P, T), \quad s.t.(1)
$$

(2)

This determines the optimal power dispatch for a single hub.

C. Hub Selection

The political structure of the region defines the modeling levels. On each level, the energy hub concept is applied for multi energy considerations. The technologies of one level form an energy hub. However, various possibilities exist to assign a technology to a level, as political units superimpose (e.g. a city is formed by a number of districts). The following hub rule is suggested to achieve a straightforward technology assignment to the levels:

A technology is assigned to that political unit (level) where the main part of its (produced or stored) energy is consumed.

The rule will not always result in a unique hub selection. However, the methodology is uncomplicated, and level interaction will cover the influences of technologies of other levels.

Recapitulating, the technologies of each level form a hub. Consequently, each level is represented by its corresponding hub. Each hub supplies the network of its sub-levels, represented by a hub network (fig.3). In the sequel, the terms “level” and “hub” will be used as synonyms.

D. Energy Exchange

The levels are connected to the multi energy infrastructure (electricity network, gas pipelines, district heat, etc.). Each level takes energy out of the net ($P$), and is able to feed energy back ($T$). The fed energy can be consumed by other levels (fig. 3). Hence, the levels interact by exchanging different forms of energy.

EXAMPLE

The multiple-level model presented above will be explained using an example. A community of three villages is considered (fig.4). One village is divided into an industrial and two residential areas. One of the residential areas consists of three, the other of two single-family houses. Consequently, the levels are community, village, district (industrial / residential area), and house. Using the hub rule, the technologies are assigned to the levels as depicted in fig.4. In the example, villages 2 and 3, the industrial area and residential area 2 do not have own generation units. They will be supplied by higher levels, and hence are modeled as loads, $L_{Vill.2}, L_{Vill.3}, L_{Ind.A}, L_{Res.2}$. Residential area 1 neither possesses own technologies, but its sub-levels do. Thus, the district level is omitted, but the house level is represented. This leads to the level structure of fig.3. Exemplarily, the hub for village 1 is depicted in fig.5.

OPTIMIZATION OF THE MULTIPLE-LEVEL MODEL

The objective of the multiple-level model is to determine the optimal power supply strategy for a region, considering different scenarios (DG, storages,...). Two optimization directions are possible:
1. Top-down optimization,
2. Bottom-up optimization.

Top-down optimization starts optimizing the highest level, and then descends to lower levels. However, top-down optimization is not a suitable way to determine the optimal power supply of a larger region. Consider fig. 3. The load of the community hub, $L_{\text{Community}}$, has to be known to determine the optimal input $P_{\text{Community}}^*$. The load $L_{\text{Community}}$ defines the input power of village 1, $P_{\text{Village1}}$. Consequently, the hub village 1 cannot be optimized any more, as its input power $P_{\text{Village1}}$ is already specified.

Bottom-up optimization starts from the lowest levels, and then ascends. First, the lowest levels are optimized (here: $P_{\text{House}}^*$). Their load profiles have to be known. The required optimal power inputs, $P_{\text{House}}^*$, define the load of the superimposed level. Then, the algorithm continues until reaching the highest level (here: community). The result is a (locally) optimal power supply strategy for the region, including all levels of energy supply.

The multiple-level model passes information about the loads and about changes in general conditions, technology infrastructure, etc. from lower to higher levels due to the optimization direction. The direction from decentralized to centralized power generation is contrary to the common procedure to start at the highest, most centralized, level, and then progress to lower, decentralized levels [20].

Applying bottom-up optimization, the load of higher levels is defined by the power requirements of lower levels. However, parts of this demand can be supplied by feeds $T$ of other hubs. In total, a level has to supply the following load:

$$L_{\text{level}} = \sum_{\text{network}} P_{\text{level-1}} - \sum_{\text{network}} T_{\text{level-1}} + \sum_{\text{level-1}} L_{\text{level-1}}$$  \hspace{1cm} (3)

The load a level has to supply, $L_{\text{level}}$, is the sum of the power requirements of its sub-levels, $P_{\text{level-1}}$ (fig.3: e.g. village 1 supplies the network of houses 1 to 3). Injections into the grid, $T_{\text{level-1}}$, contribute to the load supply. Additionally, a level has to cover the load of sub-levels without own technologies (fig.4: e.g. industrial area), $L_{\text{level-1}}$.

EXAMINATION OF THE MULTIPLE ENERGY SUPPLY

To examine the power supply of a (larger) region, the multiple-level model of the area is constructed. The levels are selected according to the political structure of the region. Power generation and storage units of each level are aggregated to energy hubs to enable multi energy carrier and technology considerations. Finally, the bottom-up optimization procedure determines the optimal power dispatch for the region. This allows the comprehensive examination and comparison of the optimal power supply strategies for different scenarios.

Sec. II presented several questions of interest regarding the power supply, the influences of distributed generation, and storage use. This section explains how the multiple-level model serves to examine these questions.

A. Question 1: Optimal Power Supply

As mentioned above, the bottom-up optimization procedure yields an optimal power supply strategy for the considered region. It cannot be guaranteed that the global optimum will be found. Usually, only a local minimum will be determined [19].

Another characteristic of the solution is the priority of lower levels. The sub-levels determine the load $L_{\text{level}}$ of a level (3). Consequently, the lower levels define the framework for the higher levels.

B. Questions 2 & 3: Centralized vs. Decentralized Technologies

The bottom-up optimization determines the optimal power dispatch for a given scenario. Changes in the framework of the multiple-level model (e.g. increase of renewable energies $R$, or different hub technology mixes) consequently alter the optimal solution. As a result, the costs for the supply strategy change. This allows the comparison of different power supply scenarios with respect to their costs (“costs” do not
necessarily mean financial expenses, but denote the value of
the objective function):  
1. The use of decentralized (renewable) energy plants
can be compared to the operation of centralized plants.
2. The performance of small and large storages can be
analyzed and differentiated.
3. The cost optimal positioning of storages and
conversion technologies can be examined.
4. The optimal assignment of a new technology to a level
can be studied.

The examination and comparison of different supply
scenarios allows the elaboration of recommendations for
action and investment for the analyzed region.

C. Question 4: (Centralized) Conventional Power Plants

The number of required (centralized) conventional power
plants can be minimized using the multiple-level model and
the bottom-up optimization procedure. Increases in renewable
energy use effect the necessity of conventional power plants.
Each hub uses renewable energy as soon as it is available at
its input. Merely the remaining power demand has to be
supplied by conventional energy carriers. Hence, increasing
renewables decrease the amount of required conventionally
produced energy. However, the installed conventional
capacity cannot be reduced by the amount of installed
renewable power because of the intermittent nature of some
renewables. The effects of extending renewable energy use
on the power demand of different levels can be evaluated
with the multiple-level model. Hence, the possible reduction
of conventional power plants can be estimated.

CONCLUSION AND FUTURE WORK

This paper presented a multiple-level model of the multi
ergy supply infrastructure of a larger (geographical) region,
like a county, or a community. The political boundaries of the
region define the levels. Each level is connected to the energy
infrastructure (gas pipelines, electricity network, etc.). The
levels exchange energy. The conversion and storage
technologies of each level are modeled as an energy hub. An
optimization procedure for the multiple-level model was
presented. It determines the optimal power dispatch for the
region.

The introduced methodology enables the examination of
the following issues:

1. Determine the optimal power supply strategy for a
region with different power generation levels and
different energy carriers.
2. Examine the effects and costs of differently sized
(renewable) energy plants and energy storages.
3. Determine the optimal positioning (centralized vs.
decentralized) of storages and conversion technologies
that will be installed.
4. Minimize the demand for (centralized) conventional
power plants.

Concluding, the presented multiple-level model is a
comprehensive tool for the examination of the power supply
of larger regions with different generation and storage
technologies.

Future work includes the validation of the proposed
approaches using case studies, as well as the determination of
a possible optimal energy supply and technology
development strategy for an example region for the year
2030.

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REFERENCES


