DISTRIBUTED ENERGY SYSTEMS SCENARIO MODELING FOR A RURAL AGGLOMERATION IN SWITZERLAND: A CASE STUDY

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ABSTRACT

Today's electricity generation and distribution systems are characterized by large-scale, centralized technologies. However, as distributed energy technologies become more readily available and affordable, their role in future energy networks must be evaluated. This study assesses the role of distributed energy technologies in a Swiss rural agglomeration using a cost optimization, energy systems modeling approach until 2050. Three main scenarios are considered: a baseline scenario in which future technology options reflect the existing infrastructure; a decentralized scenario which introduces suitable decentralized energy technologies without considering storage; and a decentralized scenario which additionally includes storage. A carbon tax is also applied in a sub-scenario which penalizes oil-based technology investments. In the baseline scenario, it is found that although the energy supply mix does not vary significantly until 2050, there is a technology shift from district heating to more decentralized and efficient wood boilers, as well as heat pumps. The main investment introduced through the decentralized scenario without storage is a run-of-river plant. This plant reduces the dependency of the village on electricity imports from the national grid by 35% by utilizing 43% of the total, local hydro potential. In the storage scenario, the run-of-river plant is replaced by a hydro dam which can achieve an electricity import reduction of 65%, alongside a 6% reduction in system costs compared to the baseline scenario. This is achieved through full utilization of the local hydro potential via seasonal storage. The introduction of a carbon tax to the model results in a significant replacement of oil boilers with heat pumps, as long as electricity network upgrade costs are not prohibitively expensive. Overall, the results indicate that distributed energy technologies (including storage) offer the potential to increase energy independence and achieve system cost savings for rural agglomerations with sufficient, local, natural resource potential in Switzerland.

Keywords: decentralized energy, distributed energy, storage, cost optimization, rural, case study

INTRODUCTION

Centralized generation technologies have long formed the beating heart of power production and distribution systems worldwide. These systems are characterized by large-scale generation, typically requiring the transmission of electricity over long distances. They have offered important benefits in the past, such as economies of scale, which have led to their widespread adoption. However, as new technologies are developed and sustainability goals come into focus on a national scale, decentralized generation strategies must also be considered as part of the design of our future energy networks.

Decentralized energy technologies (DETs) are characterized by relatively small scale applications. They offer modularity and flexibility, and are typically situated close to loads. Distributed energy strategies offer the possibility to design more energy- and cost-efficient networks [1], [2]. Local heat and electricity production may be coupled with storage options and load management, and DETs can also enable increased energy security and independence.

The purpose of this case study is to gain insight into the impacts and potential benefits of integrated, decentralized, energy-adaptive systems for a rural village in Switzerland. Both electricity and heat generation are considered. It is of interest to compare the business-as-usual case with cases introducing decentralized generation technologies, including storage options, through energy system and scenario modeling from 2010-2050.

METHOD

A least-cost optimization modeling approach is applied in this investigation. A number of scenarios are developed, modeled, analyzed, and compared in order to gain insight into the application of decentralized generation and storage systems in a rural setting.

Modeling Framework

The cost optimization model for this case study is developed using the TIMES framework. TIMES is a bottom-up, energy systems, cost optimization modeling tool developed by the International Energy Agency (IEA) [3]. It enables the development of dynamic, perfect-foresight models and determines the cost optimal evolution of capacity allocation and dispatch for specified scenarios over the modeling timeframe. The model captures the entire energy system and conversion chain. For the village in this case study, major sectors include residential and commercial/services. End-use energy demand includes building space heating, domestic hot water, and electricity.

Scenarios

Three main scenarios are developed for the case study. The baseline scenario reflects the existing energy infrastructure of the agglomeration. Only existing technologies are available as investment options. For heat generation, this includes conventional boilers (oil, wood, and electric), heat pumps, solar thermal heating, and district heating using a wood boiler and biogas CHP. Electricity demand is otherwise met by the grid (centralized production) only.

The second scenario, decentralized without storage, introduces decentralized heat and electricity generation technologies in addition to the baseline options. This includes small hydro (run-of-river), photovoltaics, wood micro CHP for individual buildings, and wood and oil CHP for district heating. These technology options have been selected based on their suitability to the agglomeration.

In the third scenario, decentralized with storage, hydro storage is considered in addition to the decentralized and baseline options of the preceding scenarios. A sub-scenario is also included which introduces a carbon tax.

Case Study Inputs and Assumptions

The annual energy demand by energy carrier is depicted in Figure 1 for the rural agglomeration in 2010. End-use energy demand for heating and electricity by sector remains constant in the model. The village is further segmented into six building categories, differentiated by function and age [4]. Hourly load curves for space heating for each building type have been defined for the study; and hydro, solar, and wood resource potentials for the village are also applied according to [4].

Technology parameters and cost input data are defined within the TIMES STEM family of models for Switzerland [5], [6] . Oil prices are adapted for Switzerland according to the IEA 4D scenario [6], and the CO_2 price is zero unless otherwise specified. If applied, CO_2 prices are used from the Swiss Energy Perspectives 2050 study, business-as-usual scenario [7]. Wood prices are based on Swiss statistics and vary with oil price fluctuations [8]. The cost for

electricity from the grid is exogenous to the model and remains constant according to current electricity prices [9].

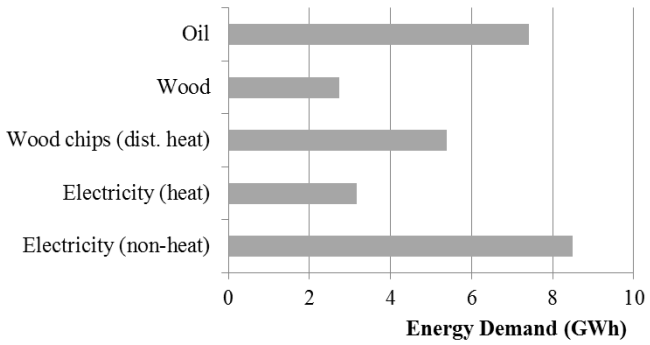

Figure 1: Annual energy demand by energy carrier in 2010 for the rural agglomeration

RESULTS & DISCUSSION

Baseline Scenario

Figure 2 illustrates the total installed capacity across heat generation technologies in the baseline scenario (a), as well as the energy supply mix (b).

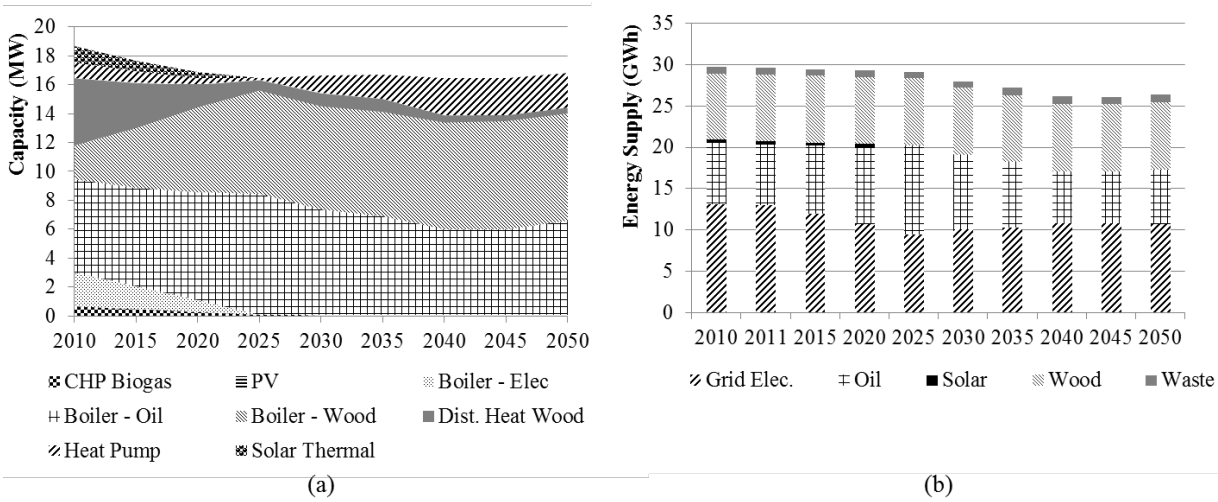

Figure 2: Baseline scenario: total installed capacity (a) and energy supply mix (b) until 2050

In the baseline scenario, oil, wood, and electricity continue to dominate the energy supply mix until 2050 with approximately the same shares as in 2010. However, a significant shift in the technology mix occurs. District heating using wood is replaced with more efficient and less costly wood boilers, electric boilers are replaced with more efficient heat pumps, and solar energy technologies are phased out altogether given the high cost of investment. The waste resource potential, although relatively small, continues to be entirely utilized by CHP biogas from 2010 until 2050. Local wood resources are also entirely utilized over the time horizon.

Decentralized Scenario without Storage

The energy supply mix and total installed capacity across heat and electricity generation technologies is illustrated in Figure 3 for the decentralized scenario without storage.

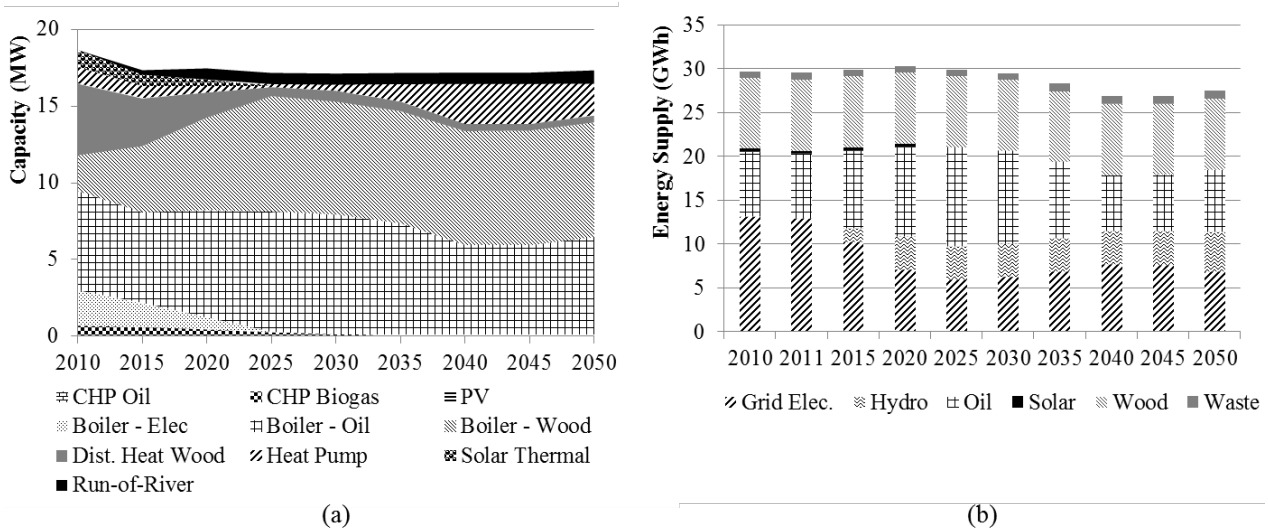

Figure 3: Decentralized scenario without storage: total installed capacity (a) and energy supply mix (b) until 2050

Similar results are found for heating technology investments in the decentralized scenario compared with the baseline case. Newly introduced decentralized heating options (CHP and micro CHP) are not selected given their high investment cost. However, investment in small hydro takes place beginning in 2015 for decentralized electricity generation. The investment in run-of-river enables a significantly reduced dependency on electricity from the grid; electricity imports are reduced by 35% in 2050 for the decentralized case compared to the baseline (centralized) case. The run-of-river plant also enables a small increase in heat pump investment. However, without the possibility of storage, only 43% of the total hydro potential is utilized (as low winter flows occur when heat demand is high, and high summer flows occur when heat demand is low). Therefore, a storage option is considered in the next case.

Decentralized Scenario with Storage

Figure 4 depicts the installed capacity and energy supply mix for the decentralized scenario with an additional hydro dam storage option.

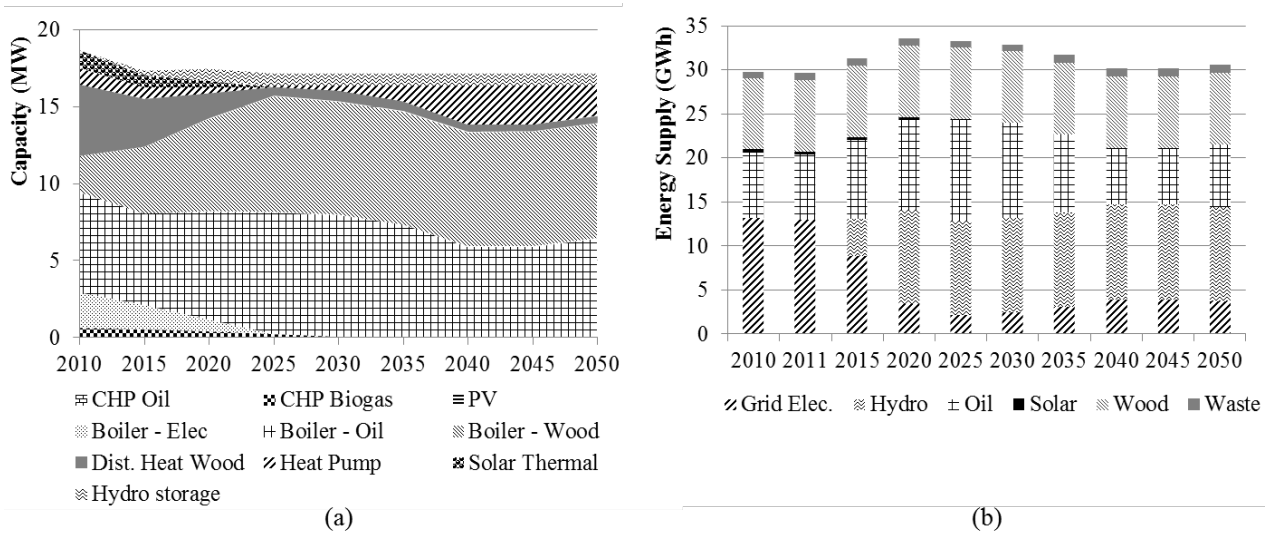

Figure 4: Decentralized scenario with storage: total installed capacity (a) and energy supply mix (b) until 2050

The run-of-river plant is replaced completely by the small hydro storage plant. The ability to store water enables 100% utilization of the local hydro potential (compared to 43% in the previous case). Water is stored over the spring, summer, and fall seasons, and is discharged during winter. The introduction of the hydro dam enables a 65% reduction in electricity grid imports in 2050 compared to the baseline scenario. This translates to a 6% reduction in total system costs. Overall, hydro storage enables a significant increase in the energy independence of the rural agglomeration in conjunction with system cost savings.

Carbon Taxed Decentralized Scenario with Storage

A carbon tax is introduced to the decentralized scenario with storage. This price varies from 15.20 CHF/ton CO_2 in 2010 to 56.70 CHF/ton CO_2 in 2050. The effect of the carbon tax on capacity investment and the energy supply mix is illustrated in Figure 5. A significant decrease in oil boiler investment and use occurs until 2040, when oil consumption is approximately 35% lower compared to the baseline scenario in the same year. Oil is replaced with heat pumps, whose capacity increases 88% by 2040 compared to the baseline scenario.

After 2040, the trend appears to reverse and heat pumps are gradually replaced with oil heating. This occurs due to the gradual retirement of the existing electricity transmission and distribution network. It is more costly to invest in upgrading and maintaining the electricity network than it is to use oil, even with an increasing carbon tax, according to the model parameters. This illustrates the significant role that the cost of network upgrades can play in defining the cost optimal system.

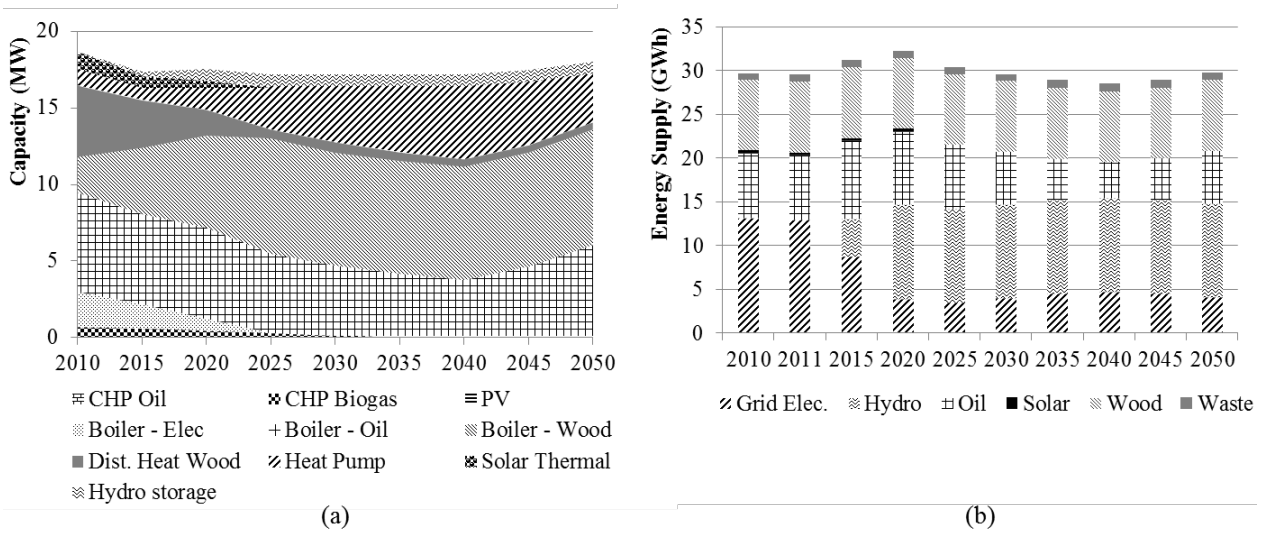

Figure 5: Decentralized scenario with storage and carbon tax: total installed capacity (a) and energy supply mix (b) until 2050

CONCLUSION

The selection of results presented in this study illustrates some of the impacts of decentralized energy technologies on cost-optimal investment decisions until 2050 for a rural agglomeration in Switzerland.

The relaxation of the baseline model to include decentralized electricity and heat generation technology options until 2050 resulted primarily in small hydro (run-of-river) investment for electricity generation. The run-of-river plant enabled a 35% reduction in electricity grid imports in 2050 using 43% of the total hydro potential. CHP and solar technology options

were not selected as cost optimal solutions, indicating that further cost reductions are needed for these technologies.

The relaxation of the decentralized model to further include storage resulted in the replacement of run-of-river with a hydro dam. Seasonal dammed storage enabled 100% utilization of the total hydro potential with a 65% reduction in electricity imports in 2050 compared to the baseline scenario. Additionally, system costs were reduced by 6%, indicating that hydro storage is a financially feasible option even for small, rural agglomerations.

The investment in CO_2-emitting oil boilers was also noticeably reduced under the implementation of a carbon tax. However, an eventual return to oil may occur if electricity network upgrade and maintenance costs are prohibitively expensive for rural applications.

Overall, it is found that system cost savings and increased energy independence can be achieved for the rural agglomeration through the full-scale utilization of local wood and hydro resources to meet energy demand. A deeper sensitivity analysis will be conducted in the next phase of this study, alongside further scenarios introducing additional storage technologies.

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