Energy Policy 96 (2016) 432–445

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

The role of decentralized generation and storage technologies in future energy systems planning for a rural agglomeration in Switzerland

Mashael Yazdanie*, Martin Densing, Alexander Wokaun

Energy Economics Group, Laboratory for Energy Systems Analysis, Paul Scherrer Institute, 5232 Villigen, Switzerland

HIGHLIGHTS

- Rural case study on decentralized generation and storage technology (DGST) benefits.
- Cost optimization model and scenarios developed to assess DGSTs until 2050.
- Small hydro and photovoltaics (PV) increase self-sufficiency of community.
- Storage enables full hydro potential usage and increased PV penetration.
- Carbon price policies effective in mitigating local fossil fuel emissions.

ARTICLE INFO

Article history:
Received 13 November 2015
Received in revised form
30 May 2016
Accepted 3 June 2016

Keywords:
Decentralized energy
Distributed energy
Storage
Rural case study
Energy system model
Cost optimization model

ABSTRACT

This study presents a framework to quantitatively evaluate decentralized generation and storage technology (DGST) performance and policy impacts in a rural setting. The role of DGSTs in the future energy systems planning of a rural agglomeration in Switzerland is examined using a cost optimization modeling approach. Heat and electricity demand for major sectors are considered. Scenarios introduce DGSTs in a stepwise manner to measure incremental impacts on future capacity planning compared to a baseline scenario. Sub-scenarios also examine the impacts of carbon mitigation policies, and a sensitivity analysis is carried out for key energy carriers and conversion technologies. DGSTs enable a significant reduction in electricity grid usage for the community considered. Small hydro with a storage reservoir and photovoltaics enable the community to become largely self-sufficient with over 80% reductions in grid imports by 2050 compared to the baseline scenario. Storage enables maximum usage of the available hydro potential which also leads to network upgrade deferrals and a significant increase in photovoltaic installations. Investment decisions in small hydro are robust against cost variations, while heating technology investment decisions are sensitive to oil and grid electricity prices. Carbon pricing policies are found to be effective in mitigating local fossil fuel emissions.

1. Introduction

Power generation and distribution systems worldwide are traditionally structured according to a centralized production strategy featuring large-scale generation and transmission capacities. Centralized generation technologies have conventionally offered economies of scale, a factor which has played an instrumental role in their widespread adoption. However, the development and uptake of decentralized generation technologies (DGTs) is also growing, and this growth motivates a reevaluation of the role of DGTs in future energy systems planning, particularly in the case of remote and rural applications.

DGTs are applied on relatively small-scales, offering modularity, flexibility, and the potential to design more energy- and cost-efficient systems. For example, transmission and distribution grid upgrades may be deferred, and local heat and electricity production may be coupled with storage options and load management. DGTs also offer the potential to increase overall energy security and independence for communities, a factor which is particularly relevant for remote, rural applications where grid access and maintenance is often costly.

In this case study, a cost optimization energy systems model is developed for a rural agglomeration in Switzerland. The model is used to identify the cost-optimal energy technology mix and operation required to satisfy electricity and heat demand across

Abbreviations: BAU, Business-as-usual; DGT, Decentralized generation technology; DGST, Decentralized generation and storage technology; FIT, Feed-in-tariff; NEP, New energy policy

* Corresponding author.
E-mail addresses: mashael.yazdanie@psi.ch (M. Yazdanie), martin.densing@psi.ch (M. Densing), alexander.wokaun@psi.ch (A. Wokaun).

http://dx.doi.org/10.1016/j.enpol.2016.06.010
0301-4215/

major village sectors until 2050. A number of scenarios are developed for the model. The baseline (or business-as-usual) scenario reflects a centralized generation scheme, while further scenarios introduce DGTs and storage options. The purpose of the study is to measure the impacts and potential benefits of deploying decentralized generation and storage technologies (DGSTs) in a rural setting in Switzerland. The impacts of policy mechanisms, including carbon taxes and feed-in tariffs, are evaluated.

Several studies have assessed the potential benefits of DGT deployment. Cost savings and efficiency gains due to transmission and distribution grid upgrade deferrals were demonstrated in (Dugan et al., 2001; Gil and Joos, 2008, 2006; Méndez et al., 2006; Poudineh and Jamasb, 2014). DGTs can also enable significant emission reductions according to the findings of (Akorede et al., 2010; Chiradeja and Ramakumar, 2004; Tsikalakis and Hatziargyriou, 2007). Two case studies focused on remote and rural regions, one in Colombia (Silva Herran and Nakata, 2012), and another in Alaska (Willman and Krarti, 2013), found that the deployment of DGTs led to cost savings and CO_2 reductions as well. Both studies used cost optimization models, but did not incorporate storage technologies into modeling. Cost savings were identified for rural electrification in South Asia in (Narula et al., 2012), and some of the considerations and criteria for the suitability of DGTs in rural applications were also explored for Sub-Saharan Africa (Szabó et al., 2011; Turkson and Wohlgemuth, 2001) and China (Holtmeyer et al., 2013).

Although the aforementioned case studies reflect differing energy systems and architectures, they each demonstrate prospective benefits of DGTs in rural applications. In contrast, this case study offers insights into the potential benefits of DGTs for a rural village in the context of a developed country, where centralized infrastructure and technology access conditions differ from those of developing nations. The cost-optimal use of local hydro, biomass, and solar natural resources is evaluated, as well as the incremental benefit of introducing storage options for use with DGTs.

2. Methodology

A number of scenarios are developed and analyzed using a least-cost optimization modeling approach in this study. Details of the modeling framework, scenarios, and assumptions are described in the following sections.

2.1. TIMES framework

An energy systems model for the rural village is developed using the TIMES (The Integrated MARKAL-EFOM System) framework. TIMES is a bottom-up, energy systems, linear cost optimization modeling tool maintained by the Energy Technology Systems Analysis Program (ETSAP) (Loulou et al., 2005). The entire energy system, from energy carrier extraction to energy conversion, can be specified using TIMES. The model then determines a cost optimal solution, including technology investment and dispatch over the modeling horizon under given scenario conditions and constraints. The objective function minimizes the total discounted system cost under perfect foresight.

The objective function to be minimized is as follows:

$$NPV = \sum_{y \in YEARS} (1+d)^{2010-y} * ANNCOST_y$$

where:

NPV is the net present value of the total cost;

$YEARS$ is the set of years in which costs are incurred;

d is the general discount rate; and

$ANNCOST_y$ is the total annual cost in year y.

The objective function is subject to several constraints, including bounds on local resource potentials and technology penetration. Demands are also balanced for each time step period and time slice[1]; for example, according to the following relationship:

$$\sum_{t \in TECHS} CAP_t * AF_{t,s} * h_s \geq DEM_s$$

where:

s represents the time slice;

$TECHS$ is the s;et of generation technologies which can satisfy demand DEM;

CAP_t is the installed capacity of technology t (kW);

$AF_{t,s}$ is the availability factor of technology t in time slice s;

h_s is the number of hours in time slice s; and

DEM_s is the exogenous useful energy demand in time slice s (kWh)

2.2. Base model

The time horizon for the rural village energy system model is 2010–2050. Major energy demand sectors are modeled, which include residential and commercial/service sectors (transportation is not a part of the study scope). Building space heat, domestic hot water, and electricity demand are considered. End-use energy demand is represented on an hourly scale for an average weekday and weekend in each season (spring, summer, fall, and winter). Five-year time steps are employed.

The village is composed of approximately 1150 inhabitants and 300 buildings. Each building is categorized by construction period and sector, which correlate to building space heating needs and efficiency.[2] Space heating demand is aggregated according to building category. The building categories are listed in Table 1, and are further detailed in (Orehounig et al., 2014).

The reference energy system for the TIMES model in the base year (2010) is illustrated in Fig. 1. This figure illustrates the existing heat and electricity supply infrastructure of the community. Additional technologies are introduced to the system in future years according to the scenarios described in Section 2.3. The village is equipped with a district heating network and is connected to the transmission grid. District heat is primarily provided by a wood boiler. A small (70 kW) biogas combined heat and power (CHP) plant which makes use of local waste also exists. Decentralized heating options include boilers, heat pumps, and solar thermal panels on a building level. Photovoltaic (PV) panels are equipped on a single residential building. Energy carriers for heat and electricity production include oil, wood, electricity, and solar energy. Seasonal heat storage and small hydro do not exist currently exist in the community.

2.3. Scenario definition

2.3.1. Main scenarios

Three main scenarios are developed for this case study: a baseline (business-as-usual) scenario, a decentralized energy technology scenario without storage, and a decentralized energy technology scenario with storage. Each scenario provides a unique set of heat and electricity generation and/or storage investment options, which have been selected based on their suitability to the village. The carbon price is set to zero in the main scenarios.

[1] Time slices represent time divisions within a year.

[2] Note that buildings which have undergone past renovations (i.e., before the base year) are assigned to their corresponding energy efficiency building category (regardless of age) in order to appropriately represent demand profiles.