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A hybrid optimization model of biomass trigeneration system combined with pit thermal energy storage

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ABSTRACT

This paper provides a solution for managing excess heat production in trigeneration and thus, increases the power plant yearly efficiency. An optimization model for combining biomass trigeneration energy system and pit thermal energy storage has been developed. Furthermore, double piping district heating and cooling network in the residential area without industry consumers was assumed, thus allowing simultaneous flow of the heating and cooling energy. As a consequence, the model is easy to adopt in different regions. Degree-hour method was used for calculation of hourly heating and cooling energy demand. The system covers all the yearly heating and cooling energy needs, while it is assumed that all the electricity can be transferred to the grid due to its renewable origin. The system was modeled in Matlab© on hourly basis and hybrid optimization model was used to maximize the net present value (NPV), which was the objective function of the optimization. Economic figures become favorable if the economy-of-scale of both power plant and pit thermal energy storage can be utilized. The results show that the pit thermal energy storage was an excellent option for storing energy and shaving peaks in energy demand. Finally, possible switch from feed-in tariffs to feed-in premiums was assessed and possible subsidy savings have been calculated. The savings are potentially large and can be used for supporting other renewable energy projects.

1. Introduction

Worldwide demand for energy is increasing; as a consequence fossil fuel resources are becoming more and more expensive, in the same time making renewable energy resources more competitive. The European Union has adopted 20–20–20 targets until 2020, which means increased energy efficiency by 20%, reduced greenhouse gas emissions by 20% and reaching a 20% share of renewable in total energy generation [1]. In the EU's 2030 framework for climate and energy policies presented in January 2014, continuing progress toward a low-carbon economy is expected [2]. The most important objective by 2030 is to reduce the greenhouse gas emissions by 40% below the 1990 level, while increasing the renewable energy share to at least 27%. In order to achieve this target, improvements in the energy efficiency are needed.

One good example in improving energy efficiency throughout the year is combined production of electricity, heating and cooling energy in trigeneration [3]. At the same time, using biomass as a fuel for the trigeneration power plant increases the renewable energy share in the overall production mix. Rentizelas et al. [4] provide an optimization model for energy supply based on multi-biomass trigeneration, covering peak demand with a biomass boiler. Puig-Arnavat et al. [5] assessed different trigeneration configurations based on biomass gasification. Borsukiewicz-Godzur et al. [6] calculated results for three variants of combined heat and power (CHP) biomass plants. A techno-economic assessment of biomass fuelled trigeneration system was made by Huang et al. [7]. Recently, Wang et al. [8] published a paper dealing with multi-objective optimization of a combined cooling, heating and power system driven by solar energy. Zhao et al. [9] analyzed the energy efficiency level for a station in China, which uses a trigeneration system. Although this is still a small-scale trigeneration system, used for a single building, interesting economic figures have been achieved, i.e. simple pay-back time of the additional investment was 5.47 years. There are also papers dealing with micro-trigeneration system such as Angrisani et al. [10], where a trigeneration system on a small-scale is assessed. Nevertheless, Kilkiş [11] developed a model for the net-zero exergy district development for a city in Sweden, which among other units includes a CHP plant with district heating and cooling system.

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In the simultaneous generation of electricity, heating and cooling energy, the system should be optimized to follow heating energy demand in order to achieve maximum efficiency of the useful energy being utilized. Please note here that due to the renewable nature of the biomass being considered, electricity generated has preference when supplying to the grid and thus, it is considered that all the electricity can be transferred to the grid at anytime. On the other hand, the feed-in tariff for electricity is the most important income for investors in trigeneration power plant. In order to be eligible to receive feed-in tariff, minimum overall yearly power plant efficiency has to be reached. One way of achieving high, relatively constant heat demand is to use dryers for reducing the moisture content in biomass. Currently, legislation in Croatia allows this, but it is questionable if it will be allowed in the future as it is not the most efficient way of using the heat energy. According to Härkönen [12], after reaching the equilibrium moisture, which will happen naturally, after a required period of time when exposed to the outside air, heat of desorption increases linearly as the moisture content is getting lower. The biomass in Croatia is delivered to the power plant with up to 30% of moisture, after which the heat needed for drying biomass increases significantly by reducing the moisture content in biomass. Moreover, the increased size of wood significantly increases energy consumption in dryers and drying can become unprofitable as shown by Gebreegziabher et al. [13]. Thus, the drying will not be considered as an option to utilize heat in this paper. As a consequence of not having a constant heat consumer, seasonal thermal energy storage will be incorporated in the optimization model in order to deal with the peak demand, as well as with large differences in heating and cooling energy demand throughout the seasons.

Currently in Croatia, for the system being assessed, only feed-in tariffs for cogeneration power plants or biomass electric power plants would be applicable, while the feed-in tariffs for trigeneration systems do not exist. Both options are at the same level for the capacities being considered in this paper. However, feed-in tariff for the pit thermal energy storage (PTES) would be of great significance for the economic feasibility of investment. Krajačić et al. [14] provided an overview of potential feed-in tariffs for different energy storage technologies. For the system being assessed, the triple tariff, as discussed in Lund and Andersen [15], would be significantly supportive toward the economic viability of the chosen system. Furthermore, neither a feed-in tariff for district heating and cooling network is available in Croatia. As shown in Rezaie and Rosen [16], district heating in densely populated regions would be a favorable investment compared to low-density residential areas. However, in this case study, a neighborhood consisting of family houses was considered.

Nevertheless, the importance of seasonal heat storage in a future sustainable energy system in Croatia was assessed by Krajačić et al. [17]. Without seasonal heat storage, critical excess in electricity production, as well as intermittency of wind power plants production, will be difficult to deal with.

Up to now, most papers have dealt with the solar thermal energy coupled with the seasonal energy storage [18–22]. Raine et al. [23] optimized combined heat and power production for buildings using a heat storage. However, storage volumes in two different scenarios had volumes of only 600 m^3 and 350 m^3. Thus, these were not large-scale seasonal storages. Rezaie et al. [24] assessed exergy and energy efficiencies of a seasonal hot water storage combined with solar collectors and boilers. When there is no instant need for heating energy, it can be stored in the large-scale pit thermal energy storage and used later when there will be need for the heating energy. In Mangold [25], it is shown that the economy-of-scale is significant till water storage volumes of 50,000 m^3. Moreover, according to Energo Styrelsen's publication [26], the economy-of-scale for the low capacity range is quite considerable.

The novel approach in this paper is a combination of large scale seasonal pit thermal energy storage and biomass trigeneration power plant. The model will be developed in order to make the most of economy-of-scale. Moreover, in order to develop the model which can be easily replicated, only residential buildings will be considered as heat consumers. From the demand side point of view this is the worst case for covering the heating and cooling load throughout the year as there is no constant need for heating or cooling energy.

Furthermore, the guidance for the design of renewables' support schemes [27] has been issued by the European Commission. Feed-in premiums, variable or fixed, were given preference over feed-in tariffs. Under the feed-in tariff, power plants do not trade any electricity on the market; they rather receive a fixed amount of subsidy per energy unit of generated electricity. On the other hand, under both variable and fixed feed-in premiums, power plant trades the electricity generated on the market, on top of which it receives a premium, which should fairly compensate the costs of generating the energy from the renewable energy sources. In the case of fixed feed-in premium, there is a larger risk placed on an investor, as the amount of subsidy on top of the market price is fixed. In the case of variable feed-in premium, a lower risk is imposed on the investor as the total amount of income per unit of energy generated is guaranteed to the investor and known in advance. Variable premium changes as the price on the market changes, keeping the total income per unit of energy generated constant. In both variable and fixed premiums, one part of the income for the investor is received from the market, reducing the total subsidy needed to be paid off by the governmental body or agency.

As Croatia has implemented feed-in tariffs as a renewables' support scheme, this paper will also estimate levels at which feed-in premiums, both variable and fixed, should be set to in order to replace the current mechanism. At the end of 2013, seven countries in the EU28 were using feed-in premiums or combination of feed-in premiums and other supporting schemes [28]. Other common supporting schemes are green certificates and tenders. So far, feed-in systems proved to be more efficient than the green certificates [29]. Potential savings in expenditure on subsidies by the government, by adopting feed-in premiums, were assessed, too.

2. Methodology

2.1. Problem definition

An investor who decides to invest funds wants to maximize profit. In a trigeneration power plant the crucial role for maximizing income is the generated electricity sold at a price set by a feed-in tariff. Consequently, the best way to maximize profit would be to produce as much electricity as possible. On the other hand, technically, the system is driven by heat demand in order to maximize efficiency. In order to satisfy both economic and technical targets, the feed-in tariff eligibility is usually constrained by a minimum overall efficiency of the power plant. In Croatia, the minimum average yearly efficiency needs to be above 50% [30] in order to receive the maximum feed in tariff, while some other examples include Austria (60%), Greece (65%) and Ireland (70%) [31]. Taking this into account, the model is possible to be adopted and used in many European countries. In order to have a constant electricity production, while still having an overall efficiency above the minimum allowed level, a relatively constant heat demand is needed. However, as it is shown that the heat demand has a strong