COMBINATION OF WIND POWER PLANTS AND DISTRICT HEATING SYSTEMS - TECHNICAL, ECONOMIC AND ENVIRONMENTAL ASPECTS

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Abstract. Due to the intermittent character of wind power, substitution of a dispatchable conventional power sources with the wind power plants is challenging and several wind integration options have been studied. This paper focuses on using surplus electricity generated by wind turbines for heat production by the heat pumps combined with the heat storage in the district heating systems. The main aim of this study is to determine the optimal capacity of the heat pump and heat storage facilities for certain capacities of the wind power plants within the power supply system. The optimal capacities are sought on the bases of technical, environmental and economic criteria. The method used is the numerical experiment with the Latvia's energy system model created within the EnergyPLAN environment. Life cycle inventory databases were used for determination of life cycle energy and material consumption.

Keywords: district heating, heat pumps, power system economics, power system modeling, wind energy integration.

Introduction

Europe 2020 strategy has set for European Union (EU) countries the targets which oblige Latvia to reduce emissions by 17 % (compared to 2005 levels) and increase renewable energy share within gross final Energy consumption to 40 % [1].

A share of electricity production from renewable energy sources (RES-E) in the total electricity consumption in 2013 was circa 47 %. [2] Considering that construction of hydroelectric power plants (HPP) is limited by a small number of large rivers in Latvia as well as by negative influence on the environment (during HPP construction, large areas are lost and also there is a spring flood risk, etc.), and that use of biomass and biogas are limited by supply of wood, wood waste and waste sources, the most promising energy resource in Latvia is wind. Use of wind power requires only the area (which after dismantling of the wind turbine may be used for the prior purpose) and sufficient wind speed.

There is no unanimity on wind power potential in Latvia and the potential of installed electric capacity of 550 MW is indicated in the Latvian wind energy handbook [3]. Ltd. "Ekodoma" and the European Renewable Energy Council (EREC) [4] believes that in the western region of Latvia it is possible to install 600 MW of wind power plants but Peteris Shipkovs (leading researcher in Institute Physical Energetics) [5] believes that it would be possible to install 450 MW onshore and another 900 MW offshore. Hence, wind resource is very promising substitute of oil, gas and coal import in Latvia.

However, integration of large amounts of intermittent wind power is challenging. Therefore, a variety of wind integration options have been widely studied all over the world. Recent studies have shown that the use of wind micro turbines in Latvia is economically unjustified due to low wind speeds [6]. Therefore, the research object of this study is large wind farms.

Since an electric power system can use limited amount of wind power due to the intermittent characteristics of this energy source which negatively affects power system stability, one of the ways of integration of the wind power into the network is to use it for a heat generation. Namely, surplus electricity generated by wind turbines could be used in the heat pumps combined with the heat storage in district heating systems of countries with high thermal energy demand during winter. This is an effective way to reduce greenhouse gas (GHG) emissions from fossil fuels in heat supply, since a heating season in Latvia lasts approximately 193-214 days per year [7].

The most appropriate type of heat pump for district heating in Latvia is the ground source heat pumps that use ground water (with temperature throughout the year within range 4-14 ºC) as a heat source. Water heat accumulators would be required very briefly since there is a very long lasting heating season [8].

The proposal of this study is to use surplus electricity (generated during periods of low demand) generated by wind power plants for heat production in ground water heat pumps. Heat pumps are combined with water heat storage which are installed in the boiler houses and combined heat and power (CHP) plants of district heating systems (see Fig.1) [9].

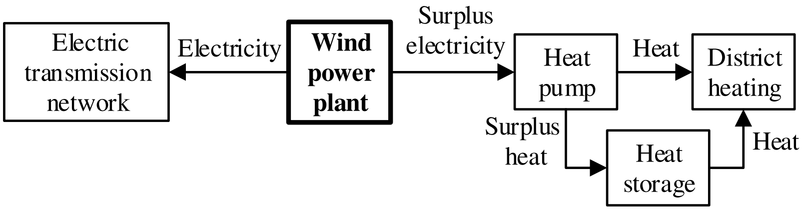

Fig. 1. **Scheme of the wind power integration into the district heating system [9]**

Materials and methods

In order to create an effective system by integrating wind-produced electricity with district heating, it is very important to determine the most effective wind turbine, heat pump capacity and thermal storage volume ratio which allows to minimize the total fuel demand, the total annual costs, the total CO_2 emissions and maximize the total RES share. The optimal solution depends on the chosen aspect - economic, technical or environmental?

For system optimization from economic aspect, it is necessary to determine the value of system`s total annual costs and select such wind power, heat pump and heat storage capacities which provide the minimum total annual costs and the maximum profit from CO_2 emission trading. Advanced energy system analysis computer model EnergyPLAN, developed by the Sustainable Energy Planning Research group at Aalborg University in cooperation with EnergyPLAN and EMD A/S [10], and which simulates the operation of national energy systems on an hourly basis, and includes electricity, heating, cooling, industry and transport sectors was used for calculations (see Fig. 2).

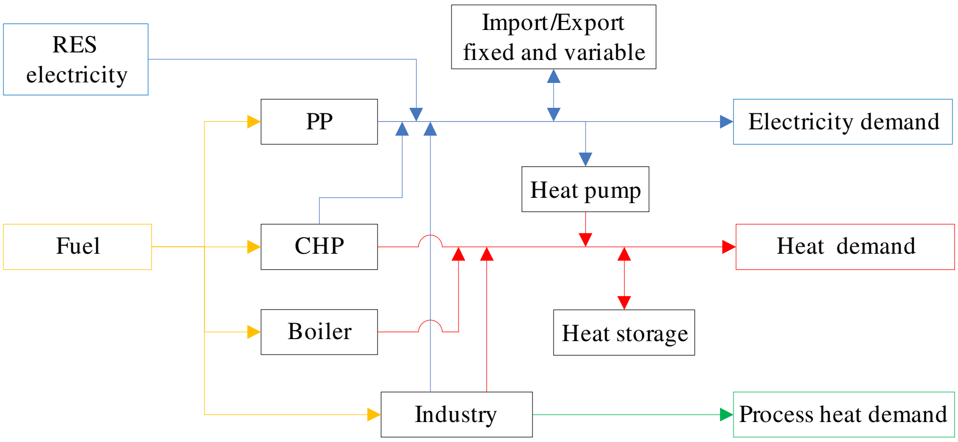

Fig. 2. **The analyzed model of the energy system**

For system optimization from technical aspect, it is necessary to determine a value of the system`s total fuel demand as this parameter characterizes effectiveness of the system operation, and select such wind power, heat pump and heat storage capacities which has the minimum total fuel demand. For system optimization from environmental aspect, it is necessary to determine a value of the system`s total CO_2 emissions and the total RES share, and select such wind power, heat pump and heat storage capacities which provide the minimum total CO_2 emissions and the maximum total RES share.

Optimization of energy systems from all three aspects - economic, environmental and technical at the same time is complicated task and requires a specific approach. The methodology for energy system optimization which is included in the algorithm was created for that purpose (see Fig.3).

Algorithm of the optimization of the heat pump and thermal storage capacities consists of six steps – energy system data collection for the computer model input, simulation of the energy system with EnergyPLAN tool, unity-based normalization for each scenario (see Eq. 1) [11], determination of the weight of each parameter for each scenario (see Eq.2) [11], calculation of grand index for each scenario (see Eq.3) [11], selection of scenario with the highest grand index.

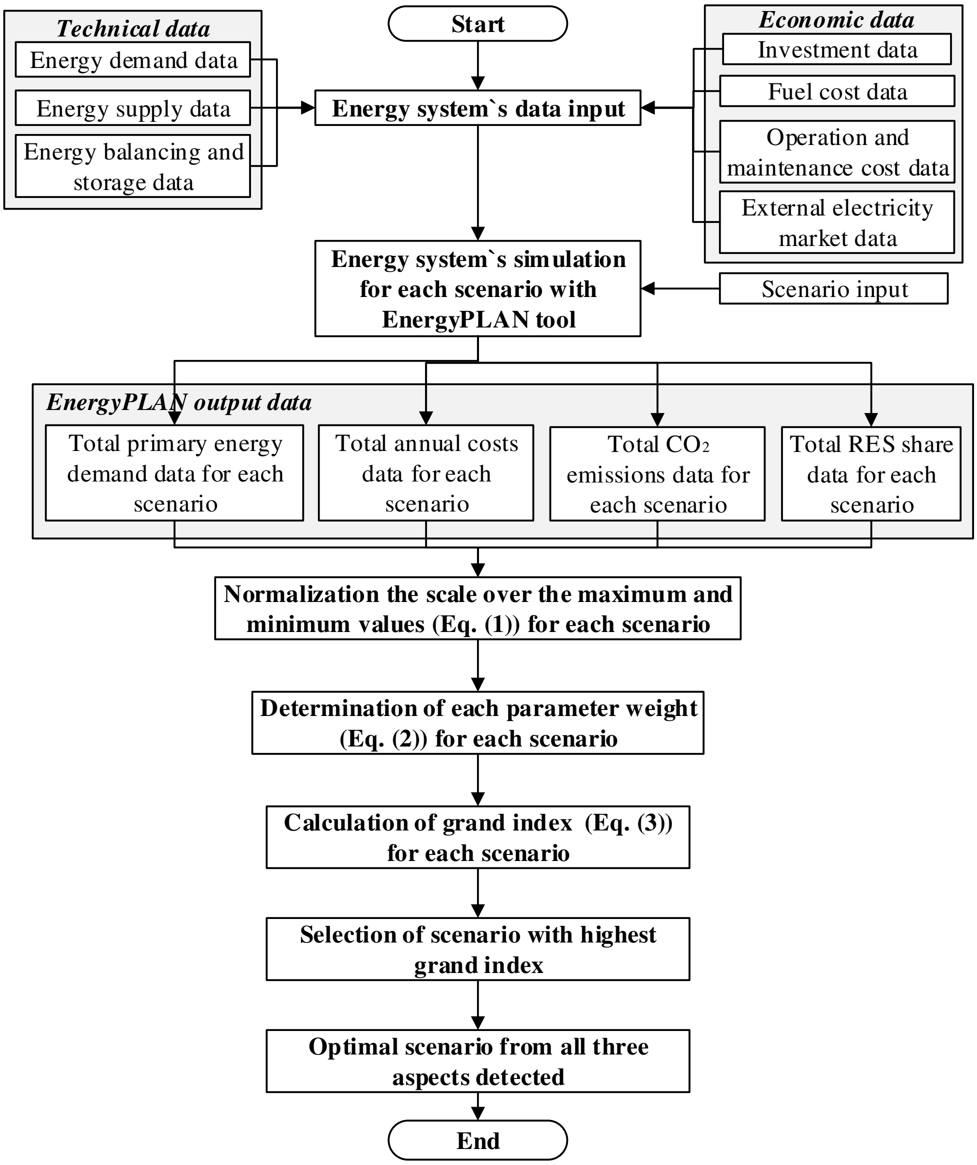

Fig. 3. **Flow chart of an algorithm of the optimization of the heat pump and thermal storage capacities**

Algorithm can be used also for selection of the optimal wind power capacity.

$$X' = \frac{X - X_{\min}}{X_{\max} - X_{\min}}, \tag{1}$$

where X' – normalized value, -;
X – original value, -;
$X_{\min}$ – minimum value in original data set, -;
$X_{\max}$ – maximum value in original data set, -.

$$X'_{PW} = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \cdot I_{PW}, \tag{2}$$

where X_{PW}' – normalized value with parameter weight taken into account (in this study it is assumed that all three criteria- economic, environment and technical are equally important, i.e., so all threeparameters are equally important.), -;
X – original value, -;
$X_{\min}$ – minimum value in original data set, -;

X_{max} – maximum value in original data set, -;
I_{PW} – parameter weight index, -.

$$I_{Grand} = \sum_{i=1}^{n} X'_{PW} \,, \tag{3}$$

where I_{Grand} – grand index, -;
X_{PW}' – normalized value with parameter weight taken into account for each scenario i, -;
I – number of particular scenario, -;
N – total number of scenarios, -.

84 scenarios were analyzed in this study (each with specific wind power, heat pump and heat storage capacity) for 7 different wind capacities (see Fig. 4).

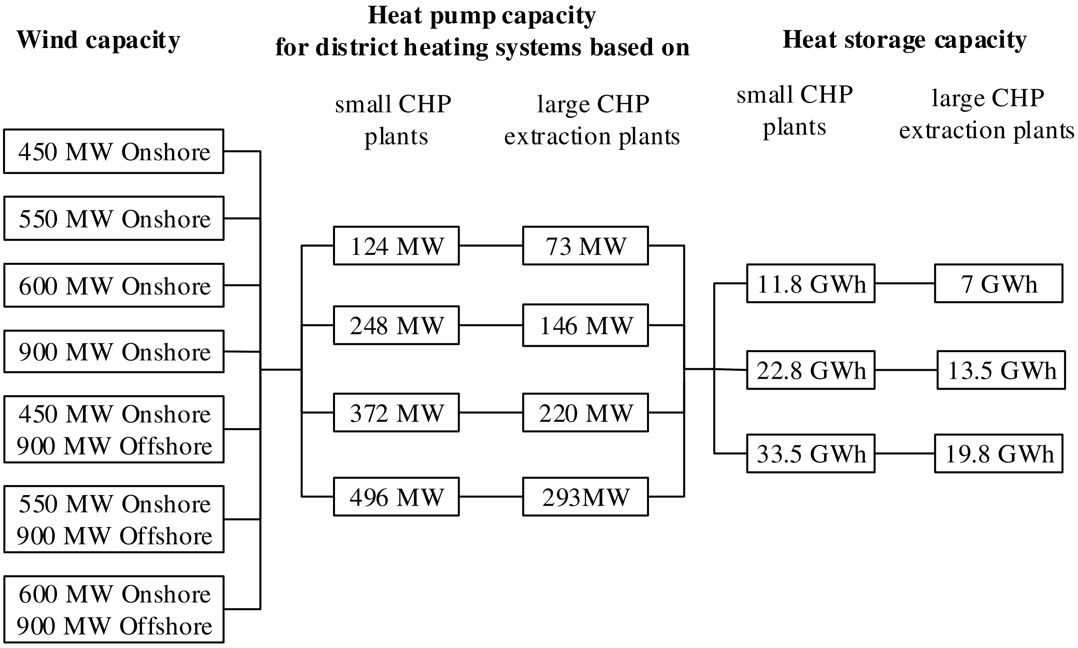

Fig. 4. **The analyzed scenarios of the energy system**

The reference (base) scenario is 67 MW onshore wind power capacity which is the installed wind power capacity in Latvia.

District heating demand is 2.583 TWhyear^{-1} for the district heating systems (DHS) based on small CHP plants and 1.527 TWhyear^{-1} for DHS based on the large CHP plants with extraction steam turbines. Latvia heating season lasts approximately 193-214 days per year [12], so the average one-day district heating demand is approximately 12.69 GWhday^{-1} for DHS based on small CHP plants and 7.5 GWhday^{-1} for DHS based on the large CHP extraction plants. Table 1 shows heat amount for district heating consumption of one-day, two-day and three-day periods taking into account that the heat storage has 7 % heat losses with the heat storage of one-day heat consumption, 10 % losses with the heat storage of two-day heat consumption and 12 % losses with heat storage of three-day heat consumption.

Table 1

Capacities of the heat storage, GWh

Heat storage for district heating consumption of	DHS based on small CHP plants	DHS based on large CHP extraction plants
One-day	11.8	7.0
Two-day	22.8	13.5
Three-day	33.5	19.8

The maximum heat capacity is 992 MW for DHS based on small CHP plants and 587 MW for DHS based on the large CHP extraction plants. The maximum installed capacity of heat pumps is to be half of the maximum total heat capacity, i.e., 496 MW for DHS based on small CHP plants and 293.5 MW for DHS based on the large CHP extraction plants. Four cases, with installed heat pump capacities of 12.5 %, 25 %, 37.5 % and 50 % from the maximum heat capacity were analyzed (see Table 2).

Table 2

Installed heat pump capacities, MW

Installed heat pump capacities as % from the maximum installed heat capacity	DHS based on small CHP plants	DHS based on large CHP extraction plants
12.5 %	124	734
25.0 %	248	146
37.5 %	372	220
50.0 %	496	293

Results and discussion

In case, when government authorities have already energy policy and set goals for the installed wind power plant capacities, it is necessary to know what the optimal heat pump and heat storage capacity is in order to integrate the wind power and district heating systems. For this purpose, this subsection is devoted to review of various wind power plant capacities which were modeled, i.e., for each wind power plant capacity the optimal heat pump and heat storage capacity selected considering economic, technical, environmental or all three aspects combination are shown.

Table 3

The optimal heat pump and heat storage capacity for various wind power plant capacities determined considering technical, economic and environment aspects

<table>
<tr><th colspan="2">Wind power plant capacity, MW</th><th rowspan="2">Heat pump capacity, MW</th><th rowspan="2">Heat storage capacity, GWh</th></tr>
<tr><th>onshore</th><th>offshore</th></tr>
<tr><td rowspan="3">450</td><td rowspan="3">0</td><td>592.1</td><td>53.3</td></tr>
<tr><td>789.5</td><td>36.3</td></tr>
<tr><td>789.5</td><td>53.3</td></tr>
<tr><td>550</td><td>0</td><td rowspan="6">789.5</td><td rowspan="6">53.3</td></tr>
<tr><td>600</td><td>0</td></tr>
<tr><td>900</td><td>0</td></tr>
<tr><td>450</td><td>900</td></tr>
<tr><td>550</td><td>900</td></tr>
<tr><td>600</td><td>900</td></tr>
</table>

As can be seen in Tab. 3, in order to ensure effective (considering technical, economic and environment aspects as equally important) power system in Latvia's case, it is necessary to install heat pump with capacity higher than circa 790 MW and heat storage larger than 36 GWh.

An impact of the optimal scenario on the total annual costs, total CO_2 emissions and total RES share in comparison with the base scenario is shown in Table 4.

The lowest total CO_2 emissions and the highest total RES share can be achieved with wind power plant capacities of 600 MW onshore and 900 MW offshore. The lowest annual costs are in case of 450 MW onshore wind power plant. The highest decrease in the total primary energy is in case with 900 MW onshore wind power plant capacity.

Table 4

Impact of the optimal scenario on the total annual costs, total CO_2 emissions and total RES share in comparison with the base scenario

Wind power plant capacity, MW		Increase in		
onshore	**offshore**	**Total annual costs, %**	**Total CO_2 emissions, %**	**Total RES share, %**
450	**0**	**4.35**	-5.99	5.21
		5.74	-5.99	5.21
		5.85	-5.99	5.21
550	0	6.05	-6.41	6.64
600	0	6.15	-6.69	7.58
900	0	6.86	-7.66	11.85
450	900	10.52	-8.77	18.48
550	900	10.80	-8.91	19.43
600	**900**	10.94	**-9.05**	**20.38**

Conclusions

In order to ensure effective power system by installing 450MW onshore wind power plant capacity in Latvia's case, it is necessary to install heat pump with capacity higher than circa 790 MW and heat storage larger than 36 GWh.

The lowest total CO_2 emissions and the highest total RES share can be achieved in case of 600 MW onshore and 900 MW offshore wind power plant capacities. The lowest annual costs are in the case with 450 MW onshore wind power plant. The highest decrease in the total primary energy is in the case of 900 MW onshore wind power plant capacity.

The results can be used practically by the district heating and power supply companies as well as for development of energy policy by government authorities.

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