Design for renewable energy systems with application to rural area in Japan

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Abstract

This study is based on optimization and simulation modeling of renewable energy system in rural area in Japan. The model we have designed provides an optimal system configuration based on hour-by-hour data for energy availability and demands. This model produces a minimum cost design for an energy system as well as the capacities of each technology. This tells us how to configure the system to meet a specific set of demand and what such a system will cost. It consists of renewable resources and backup power stations to supply electricity and heat into industrial, commercial and residential end users. In this study, the electricity market is supplied by the wind electricity, photovoltaic (PV), and backup generators (which is equivalent to un-served load in this model), and the heat market is supplied by biomass co-generation, geothermal heat pump (GHP), petroleum, and gas. The result of our analysis clearly shows the following:

1. About 79 percent reduction in carbon dioxide (CO_2) emission can be obtained fairly inexpensively with renewable energy system.
2. PV can be used to reduce the need for peak fossil generation since the sun mostly shines during peak demand hours.
3. Combining the wind electricity with GHP, we can configure the optimal renewable energy system.

1.Introduction

In 1990's, global environment concerns have been increasing. In particular, world attention has been focused on global warming caused by greenhouse gases such as CO_2. In 1997, the 3rd session of the conference of the parties (COP3) was held in Kyoto, and the Kyoto protocol required reduction of greenhouse gases was adopted. In order to reduce greenhouse gases, clean energy is important. Because renewable energy sources don't discharge any emissions, renewable energy is expected to play a major role in the 21st century.

What is more, since the structure of Japan's energy supply depends heavily on imported fossil fuels, with its attendant risks to energy security, it is necessary to reduce reliance on fossil fuels to achieve a stable energy supply. As an alternative of fossil fuel, renewable energy is relatively unconstrained. It has high sustainability and potential to handle a large share of energy supplies in the future. In order to promote installation of renewable energy systems in Japan, a renewable portfolio standard will be implemented commencing in 2003.

However, renewable energy is not efficiently used because of the difficulties in operation. Renewable energy has low energy conversion efficiency and low load factor. Moreover, a large land area is necessary to produce enough power to meet the demand. In addition, energy output from renewable source is unreliable because renewable energy such as

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PV and wind are dependent on local climate conditions. For these reasons, utilization of renewable energy at urban area is not reasonable. On the contrast, the utilization of renewable energy at rural area is promising to supply electricity and heat at reasonable cost.

In this study, we have designed a renewable energy system focusing on a rural area in Japan. It shows a combination of renewable and conventional energy technologies. This study optimizes the design of a renewable energy system for a specific location and finds the most economical operation.

2.A renewable energy system in a rural area

A renewable energy system, which we have designed here, is composed of some renewable sources, and targets a small area such as a village. The system supplies energy to rural area by using renewable sources. The system configuration of renewable energy system varies with site location. Because renewable energy are generally intermittent, it may happen that renewable power is not sufficient to meet the regional demand in some hours. Therefore, the proposed energy system is connected to the distribution grid, and buys electricity as backup whenever the renewable supply is insufficient. In contrast, excess electricity is sold to the electric utilities through the grid.

In our study, we have targeted a local village with a population of 9,000 in Iwate prefecture in northern part of Japan, examining the possibility of installation with four kinds of renewable sources, such as PV, wind electricity, biomass co-generation and geothermal heat pump. These renewable sources are combined with conventional energy systems in which electricity is supplied by the distribution grid, and heat is supplied with petroleum or gas. We have modeled a renewable energy system in rural area using several system modules. The network of the system is shown in figure 1. At the market node which is expressed in the shape of ellipse in figure 1, energy sources at end-users are decided based on the price of energy, and the selected energy is provided to the village. By this means, the most economical energy system will be configured and optimized.

3.Result of the analysis

3.1 Electricity supply

The changes in the quantity of electricity supply are shown in figure. 2. During windy period, the wind generator is running well and the wind electricity constitutes a fairly large portion of total electricity which is supplied to the village. When wind electricity cannot provide enough power to meet the electricity demand, grid electricity will make up for a deficiency. Figure 3 represents the changes in the quantity of electricity supply during wind-less period. The portion of grid electricity is large in the figure, as the production of wind electricity is not sufficient.

The changes in the price of electricity are shown in figure 4. During the windy period, the price of wind electricity hovers around $4,000/MWh, and the price is much lower than that of other power generation. At the electricity market, the lowest price is preferred to supply electricity to consumers. Then the electricity market selects wind electricity as the lowest price, and most of the electricity is provided by wind turbines. However, during wind-less period, the production of wind power goes down and the price of wind electricity rises suddenly because of shortage of wind electricity. If the price of wind electricity becomes higher than that of other power generation, market selects other types of electricity to meet the demand at the village. In our study, alternative power means PV and grid electricity. According to figure 4, the price of PV hovers from 23,500 cents/MWh to 27,500 cents/MWh, while the electricity price of grid electricity shows 23,333 cents/MWh. Under this condition, the electricity market selects grid electricity among alternative electricity. Therefore, in case that wind electricity is in shortage and can't meet all the electricity demand, grid electricity makes up for a deficiency.

3.2 Heat supply

The changes in heat supply produced by different energy sources are shown in figure 5. Geothermal heat pump (GHP) and petroleum are main heat source. Figure 6 represents the changes in heat price. Because the power source of GHP is electricity, the price of heat by GHP is influenced by the electricity price. Compared with the fluctuation of the electricity price, price fluctuation of GHP heat goes along with fluctuation of the electricity price. In the case of low electricity price, the price of GHP heat is also low. While in the case of high electricity price, the price of GHP heat is also high. During the lower heat price of GHP, the price hovers from 1,000 cents/MWh to 2,000 cents/MWh. Compared with the prices of other heat sources, the price of GHP is the lowest. As a consequence, heat produced by GHP is supplied to the village. On the contrary, when the price of GHP heat is high, the price hovers from 6,000 cents/MWh to 7,000 cents/MWh. Because the price of petroleum heat is 4,728 cents/MWh during that time, the price of GHP heat becomes higher than that of petroleum. Therefore, the heat market selects not GHP but petroleum as a heat source. Because the prices of other heat sources are higher than petroleum, petroleum is selected as a substitution of GHP by priority. For these reasons, when wind electricity meets all the electricity demand in the village, heat is supplied by GHP, and when the production of wind electricity falls down, petroleum is selected as a heat source.

3.3 Optimal system configuration

Figure 7 represents a capacity of renewable source as a result of economical optimization for renewable energy system. In terms of electricity supply, the capacity of PV is 1.0 MW, and the capacity of wind electricity is 18.0 MW. The share of wind electricity is very large, accounting for more than 90%. In term of heat supply, the capacity of biomass, GHP and petroleum is 0.6 MW, 19.1 MW, 4.3 MW, respectively. Since the gas for heat supply has not been installed in the system, the capacity of gas shows 0. Consequently, optimal renewable system is configured from a large amount of wind and GHP, and a little PV, biomass and petroleum.

It becomes clear that the renewable energy system in the village is largely influenced by the wind condition. At windy location, installed capacity of wind electricity is large, and that of PV is small. Then, we see how the reduction of specific capital costs (SCC) of PV has an impact on the installed capacity of PV. Figure 8 represents the SCC of PV and the installed capacity of PV. We have reduced the SCC of PV from $5,000/kW to $1,500/kW, however, installed capacity of PV has not much changed. This reason is that the load factor of PV is approximately 10%, and the load factor of wind electricity is around 25%. In order to produce same quantity of electricity, PV needs twice and more installed capacity than the wind turbine. Even if the SCC of PV is lower than that of wind electricity, the capital cost of PV is more expensive than that of wind electricity. This is why installed capacity of PV doesn't change.

In the case of $1,000/kW, electricity production of PV increases about three-fold. Compared with the production of wind electricity, the share of PV is still low. As the PV generates only during daytime, it contributes to supply during peak-load time. As a result, wind electricity which can generate through the day long, though it depends on wind condition, is large in installed capacity.

3.4 CO_2 emission

CO_2 emission from renewable energy system in the village and that of conventional energy system are shown in figure 9. For the calculation of CO_2 emission, we have used carbon emission factor which Japan's Ministry of Environment released. In the case of conventional energy system, annual CO_2 emission reaches 6,853 tons-C/yr. While in the case of renewable energy system, annual CO_2 emission reaches 1,460 tons-C/yr. The renewable energy system which we have designed here can reduce CO_2 emissions by 79%, and contribute in significant reduction of fossil fuels combustion.

3.5 Economic aspect

Figure 10 represents comparison between annual cost of renewable energy system in the village and that of conventional energy system. The cost includes fuel costs, operating costs and capital costs. Annual cost of conventional energy system shows $11,216,574/yr in our calculation. While annual cost of renewable energy system in the village shows $9,566,794/yr. As a result, the renewable energy system can reduce the annual cost by 15%. Over-generated electricity is sold to electric utilities for $930,683. Considering this amount of sales, the renewable energy system can reduce annual cost by 23%.

Furthermore, if carbon tax is imposed in the future, renewable energy system would be more favorable than conventional energy system in terms of annual cost, because CO_2 emission of former is less than that of latter as mentioned above.

4.Conclusion

We have examined the possibility of installation combining four types of renewable energy, such as wind electricity, PV, biomass co-generation and geothermal heat pump (GHP). It becomes clear that the wind electricity and the GHP are necessary in order to optimize renewable energy system with economical way in rural area. On the contrary, PV and biomass co-generation are not installed in the proposed system. This is because the capital cost of wind electricity is lower than that of PV, and there is little difference between ancillary operating cost of wind electricity and that of PV. The price of wind electricity is quite low, and hovers from 3 cents/kWh to 5 cents/kWh, whereas current price of grid electricity that is used in general household is 23.33 cents/kWh in Japan. Wind electricity can supply electricity to rural area at the one-fifth of current electricity price. This cheap electricity allows GHP to supply heat at low price because the power source of GHP is electricity. In terms of CO_2 emission, renewable energy system in rural area can reduce CO_2 emission by 79% as compared to conventional energy system. In terms of annual running cost, renewable energy system in rural area can reduce the cost by 15% as compared to conventional energy system. Considering the surplus amount of sales to grid utilities, annual cost can be reduced by 23%.

In concluding, the combination of wind and GHP configures optimal renewable energy system. Compared to conventional energy system, CO_2 emission and annual cost are reduced by utilization of optimal renewable energy system. In order to install PV or biomass co-generation into the renewable energy system, it is necessary to reduce initial cost by mass production and to reduce the differences in the energy price by political measures such as substitution or taxes.

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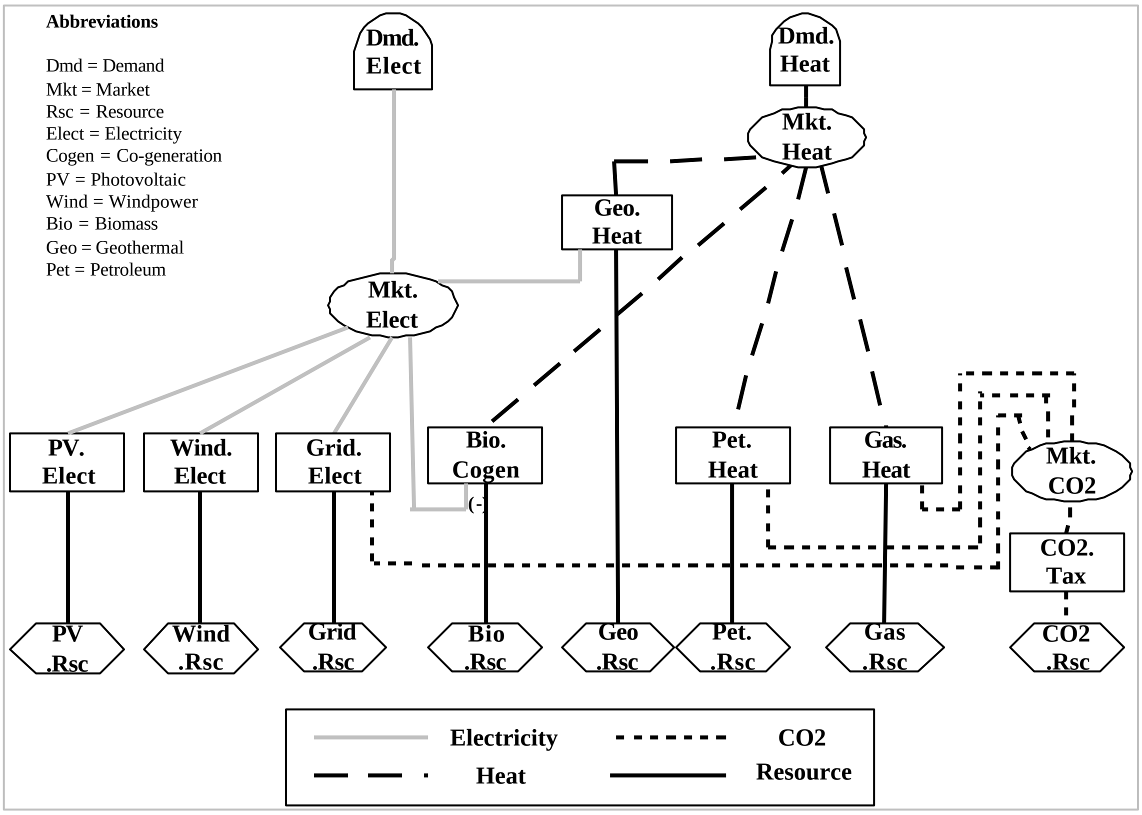

Fig. 1 Network for renewable energy system in rural area

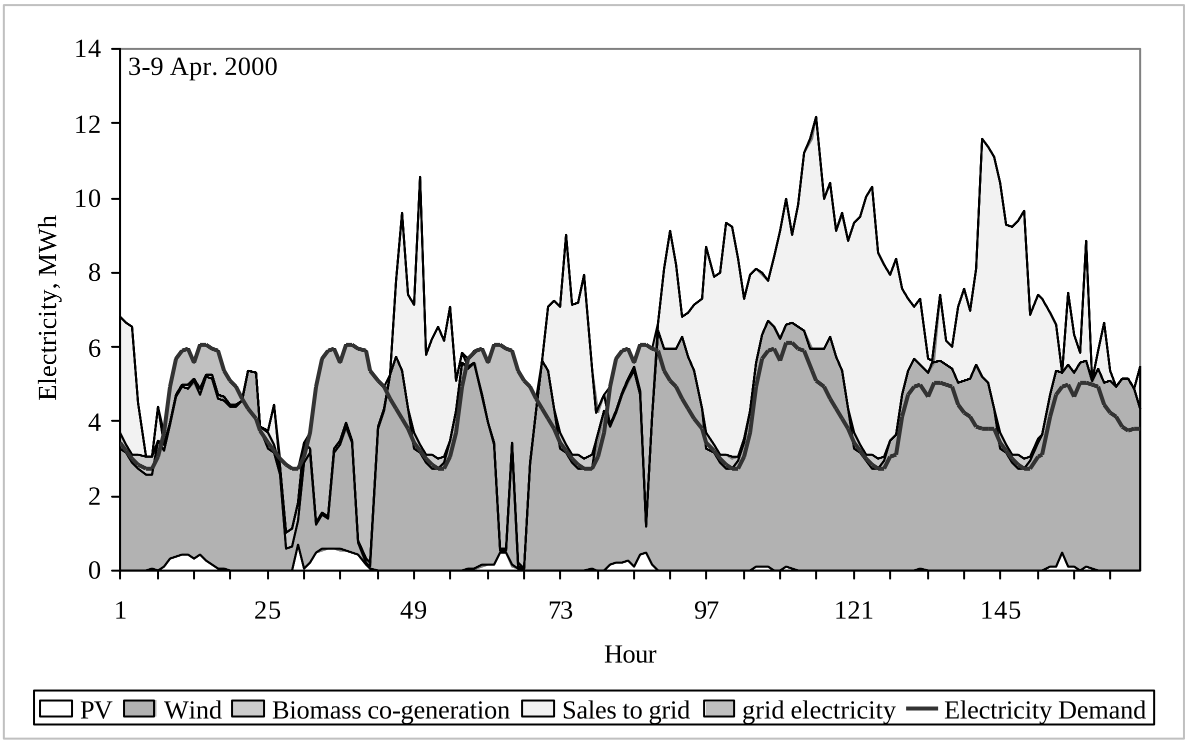

Fig. 2 Electricity generation(windy)

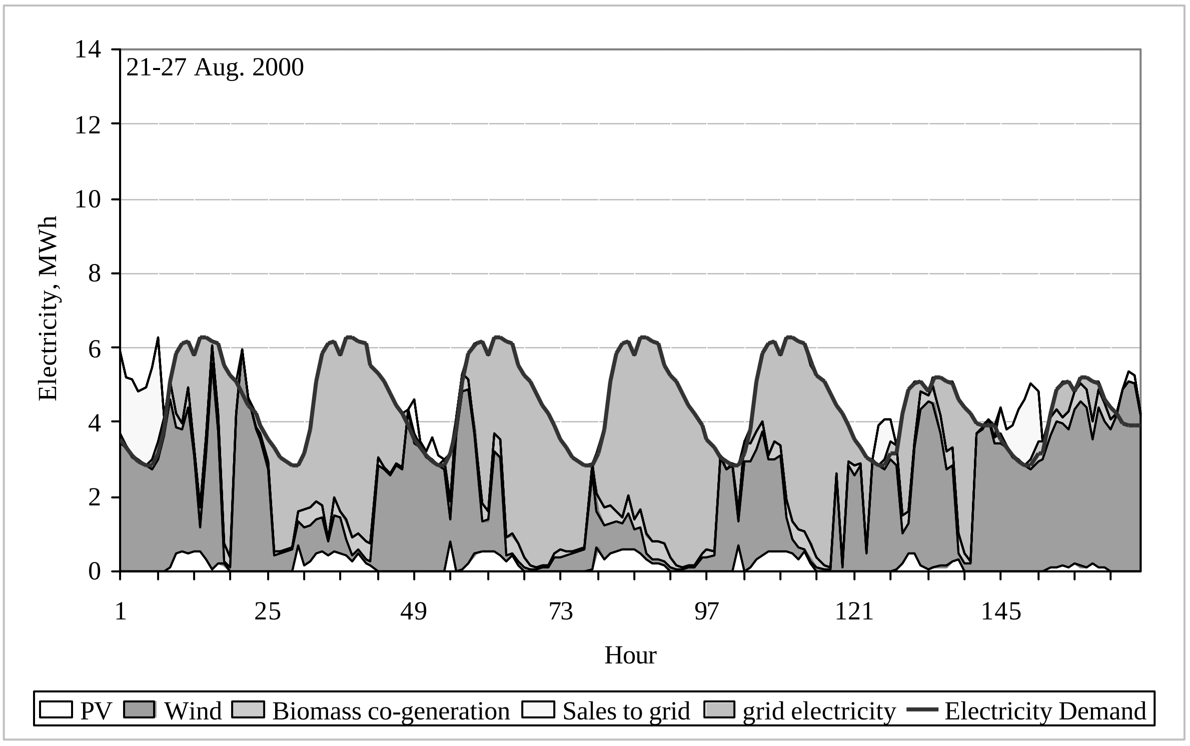

Fig. 3 Electricity generation(wind-less)

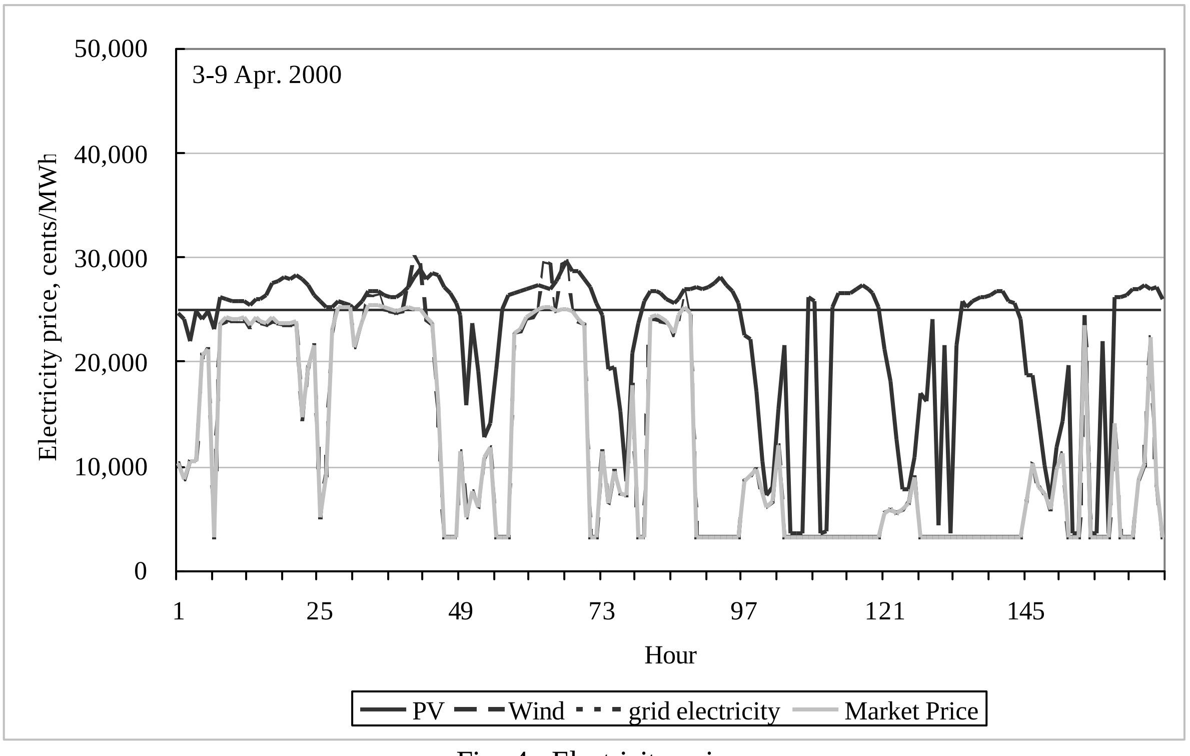

Fig. 4 Electricity price

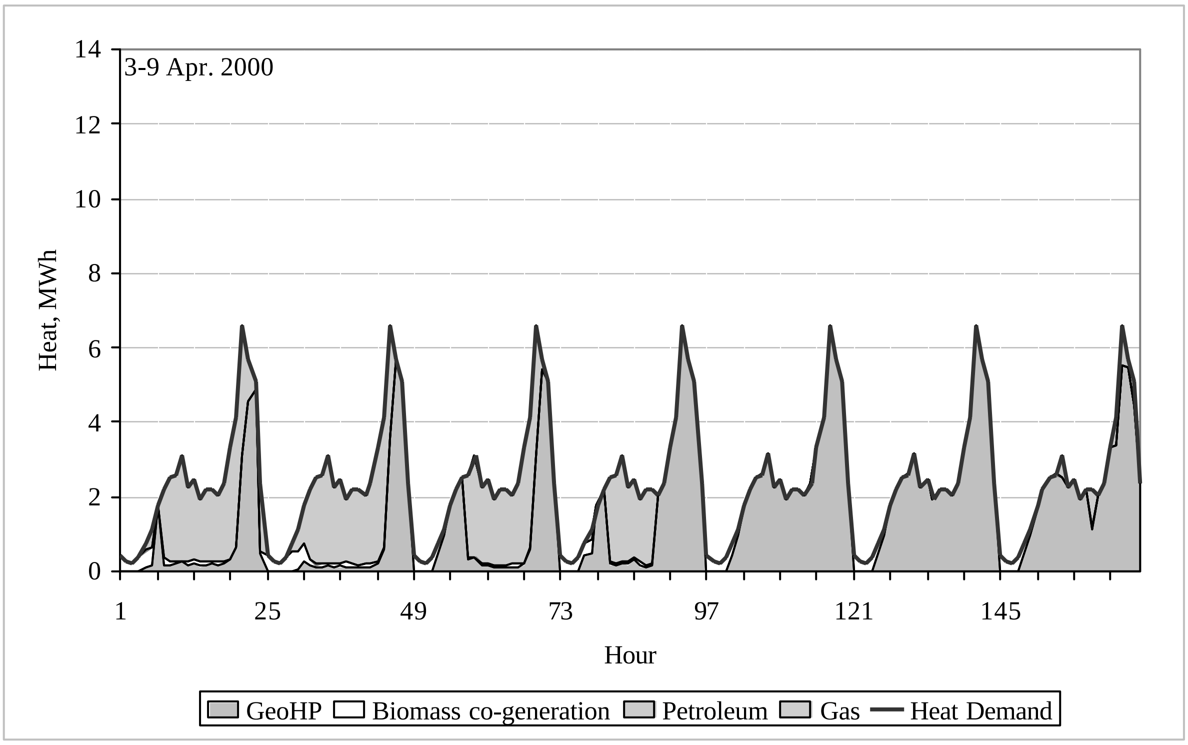

Fig. 5 Heat supply

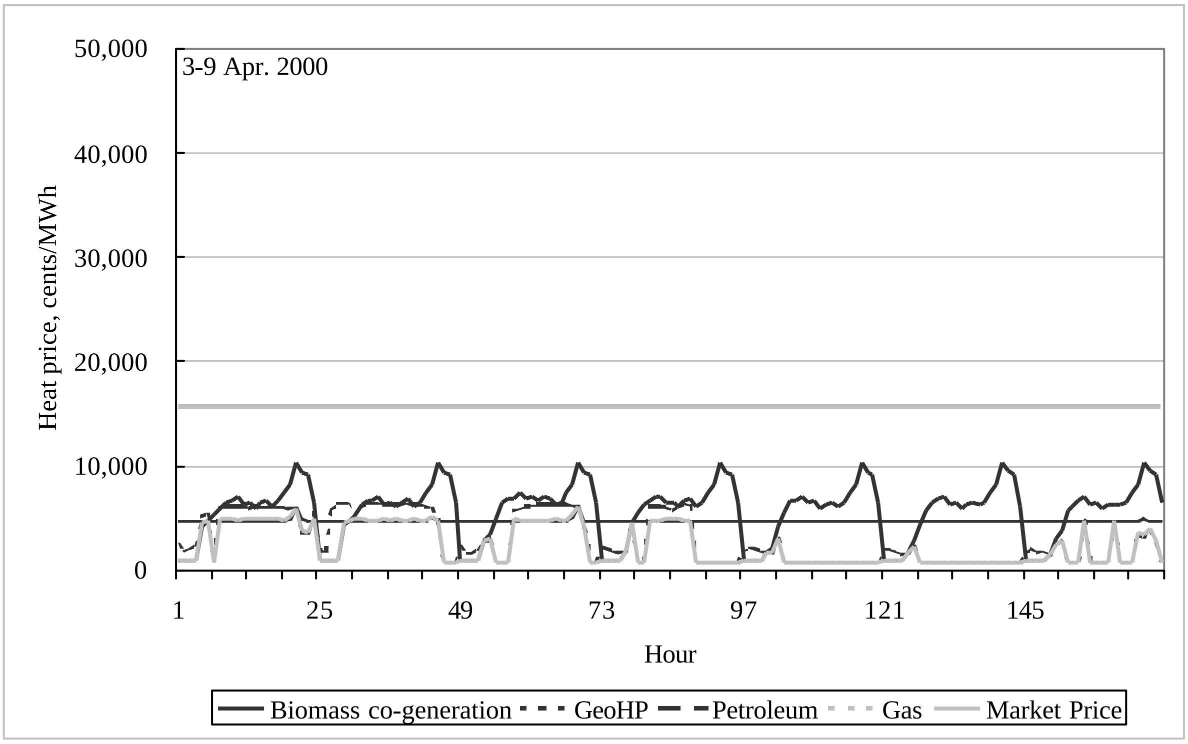

Fig. 6 Heat price

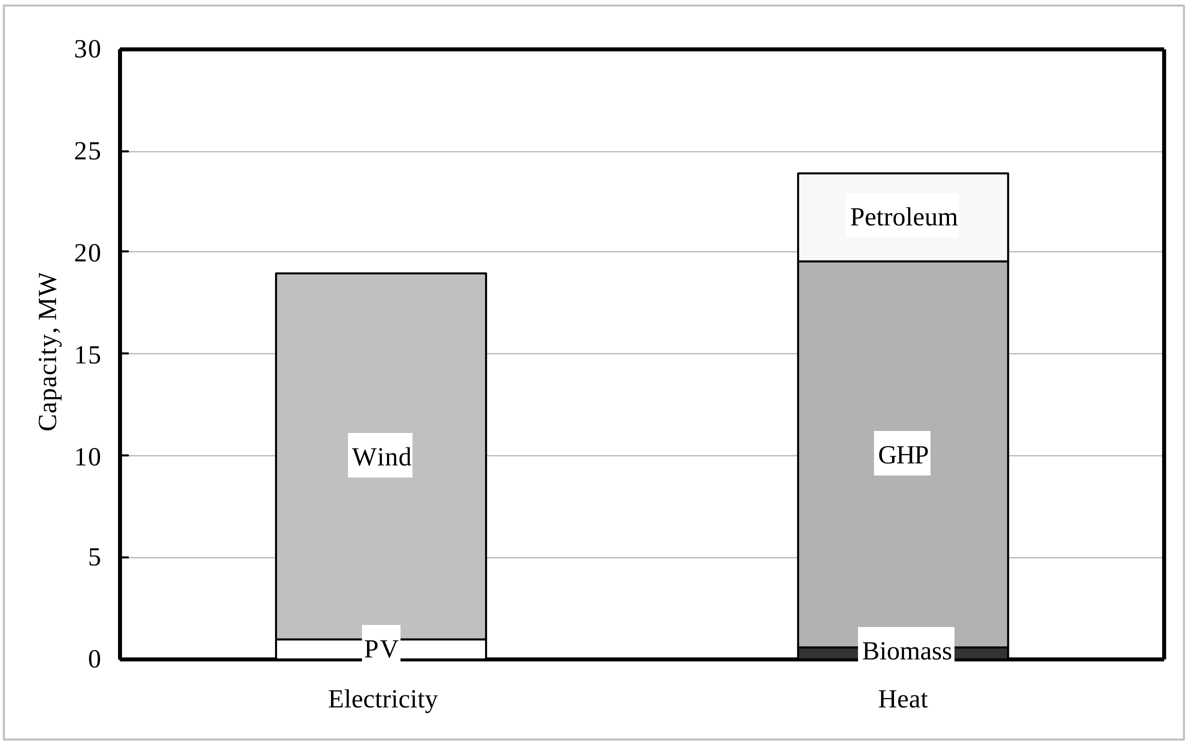

Fig. 7 Optimal system configuration

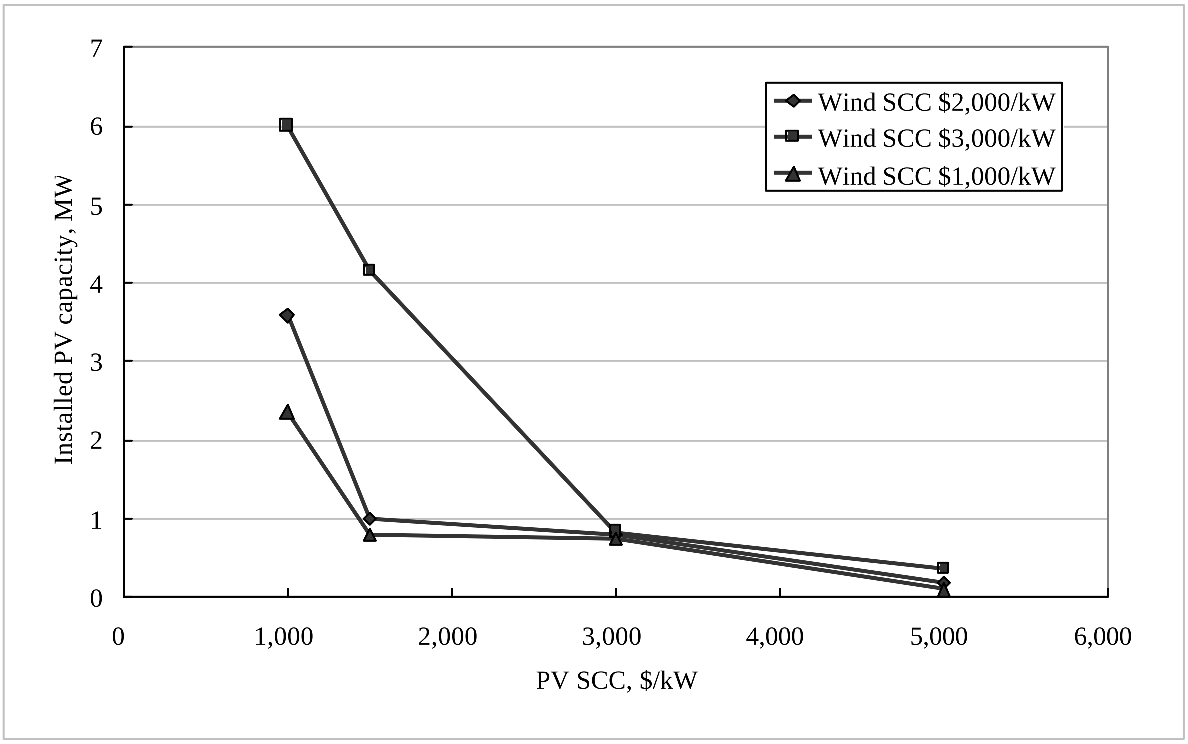

Fig. 8 Capital costs of PV and its installed capacity

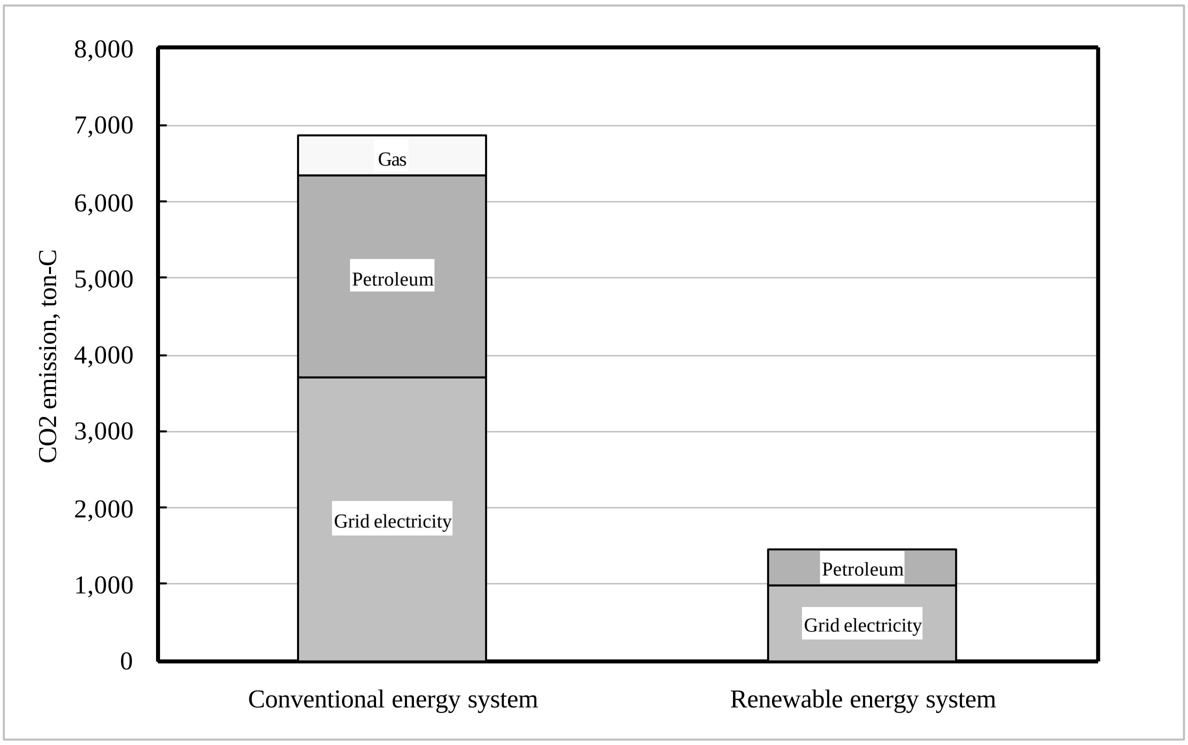

Fig. 9 CO_2 emission

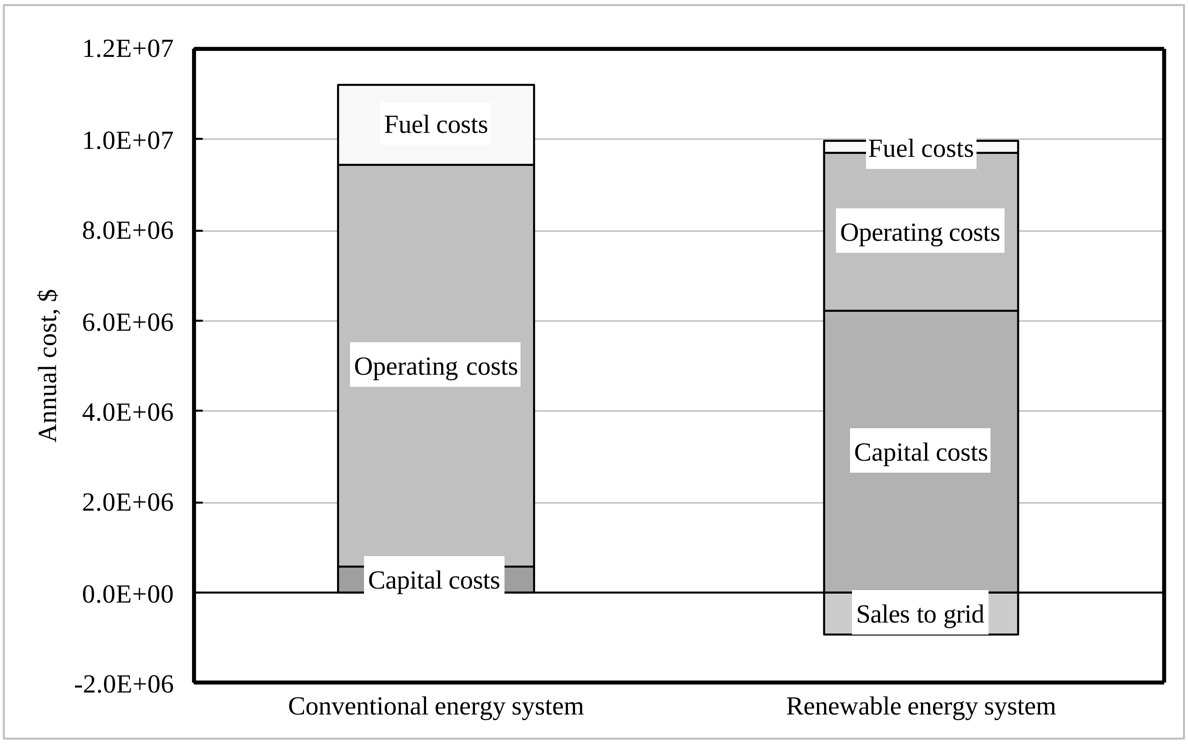

Fig. 10 Annual cost