PV/WIND HYBRID SYSTEM FOR LOW EMISSION COMMERCIAL BUILDINGS OF THE FUTURE - A CASE STUDY IN NORWAY

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1. Introduction

Buildings are responsible for 40% of energy consumption and for 33% of direct and indirect greenhouse gas emissions in Europe (International Energy Agency, 2008). Energy efficiency in the built environment has a large potential for decreasing dependency on fossil fuels, and can contribute significantly to a low-emission development strategy, which is indispensable to sustainable development. By using commercially available, cost-effective technologies and by producing electricity from on-site renewable energy sources, building energy consumption could be reduced.

The European Union has set up new standards for future buildings in order to achieve better energy efficiency and lower the demand, such as the "Energy Performance of Building Directive Concerted Action", EPBD (EPBD-CA, 2005). The EPBD requires all EU countries to enhance their building regulations and to introduce energy certification schemes for buildings. Moreover, the European Parliament and Commission declared that by 31 December 2020 all new buildings must be nearly zero energy buildings. To achieve this goal, the use of energy from renewable sources is significant.

In Norway, noteworthy work has been done in strengthening the building codes towards a reduction of the use of energy in buildings. Since Norwegian buildings are commonly heated by electric radiators (99% of the energy is produced with hydropower), electric power consumption per capita is much higher than in other countries. The increase in electric energy production from renewable energy sources used on-site in the building sector is beneficial for achieving a more distributed electrical system with reduced energy transmission losses and lowered peak demand for the heating load.

2. Objectives

The objective of the work presented here is the study of a PV/Wind hybrid system for a low emission commercial building (Rogaland Energisenter, RES, Fig.1) located in Southern Norway (Bjerkreim, Rogaland county, coordinates 58°35' N, 6°4′ E). The commercial building will host an energy center and aims to reach a class A energy label on buildings, which means an energy consumption lower than 84 kWh/m^2 per year (Norges vassdrags og energidirektorat, 2010), and has a total interior surface area of 3500 m^2. The final architectural details, the internal loads and the number of occupants are not known at this stage; hence, assumptions will be made according to national and international standards. As the owner of the building wants to inquire about the feasibility and differences between a grid connected hybrid system and a stand-alone system in Norway, the respective results are included here, despite the fact that the stand-alone option would not be necessary due to the grid-supply conditions. The systems have been evaluated using the simulation software HOMER (Hybrid Optimization Model for Electric Renewables, 2010).

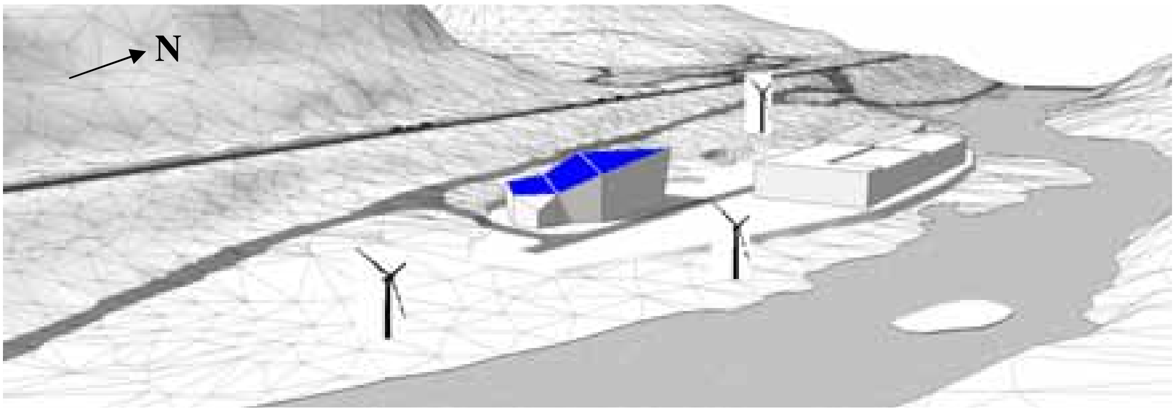

Fig. 1: Preliminary sketch of the RES building (on the left). The blue area is assumed to be covered with PV panels. Three possible locations of the wind turbine are shown.

3. Methodology

The following method has been used:

- Load profile assessment: all the ordinary loads in a commercial building will be listed and analysed. Calculations for each electrical load will be performed to achieve a final load profile that fits with a typical office building demand. The load profile will be used as an input for the hybrid system simulation software.
- Resource assessment: the renewable energy potential from the local sun and wind sources will be assessed, taking into consideration the possible constraints and site location.
- Modeling and optimization of the hybrid system: a grid-connected and a stand-alone case will be modeled and optimized using simulation software. The inputs for the simulation are the load profile and the assessed solar and wind resources. Different scenarios will be tested to perform a sensitivity analysis on certain parameters.
- Comparison of results: results from the simulation will be commented and compared with literature values for validation.
- Economical analysis: an economical study will be performed on the possible scenarios, taking into consideration the energy flows to and from the grid.

3.1. Load profile

The load profile evaluates the different electric loads that are commonly present in commercial buildings: lighting, office equipment (PCs, printers, etc.), fans for ventilation, tap water heating, space heating and cooling. The assumptions are 246 working days per year and 12 hours of office work per day.

The electricity demand for lighting was calculated for each season, taking into account the percentage of clear sky days (NASA, 2010) when no lighting is needed except for corridors and restrooms (assumed to represent 30 % of the total surface area). The standard power demand is 15.8 kWh/m^{2}a (Dokka et al., 2009). The calculated average lighting demand is 11.64 kW for summer, 12.40 kW for winter and 12.19 kW for spring/autumn. The difference between summer and winter power requirements for lighting is small due to the low frequency of clear sky days during the different seasons in this region of Norway. When the sky is overcast or cloudy the use of artificial lighting is necessary for office work.

Low energy consumption office equipment is assumed (Energy Star, 2010; LCD Monitors, 2010), with a specific load of 7.5 W/m^2. The resulting yearly office equipment load is 22.14 kWh/m^{2}a. During the night, the server in the data centre is assumed to be operating continuously at all times of the year. An electric demand of 3 kWh/m^{2}a is assumed (Mariager, 2009).

The use of mechanical ventilation is assumed to occur during working hours and in the office area only (70 % of the total area). The ventilation energy demand is set at 5 kWh/m^{2}a (Sustainable Solar Housing, 2006).

Water heating can be supplied by solar thermal panels in summer, whereas in winter an electric heater will be used. During autumn and spring, half of the winter load will be assumed. The consumption of hot tap water is set at 5 kWh/m^2 per year (Norsk Byggtjenestes Forlag, 2007). For the RES building we assume 50 % of the hot water demand is provided by solar thermal power (Grini et al., 2009).

The power needed for space heating should take into account solar gains through glazing and walls, heat losses (from the whole building) and heat gains (from occupants, electrical equipment and lighting). The solar gain will be neglected in this calculation because no detail about the building architecture is available. The other assumptions for the calculation are: desired indoor temperature 18°C, and the daily average outdoor temperature for Eik (the closest meteorological station) measured during 2008 is used as a reference for T_{out} (eKlima, 2010). (More reliable estimates can be obtained by including long-term weather data).

The calculated daily heating demand [W/m^2] is:

$$h_{demand} = h_{gain} - \left[k_{loss} \cdot \left(18°C - T_{out}\right)\right] , \tag{1}$$

where h_{gain} is the heat gain value (a value of 5.4 W/m^2 is assumed here according to (Dokka et al., 2009)), k_{loss} is the heat loss coefficient (an average value of 0.5 W/m^{2}K (Dokka et al., 2009) is assumed here; it depends on the thermal performance of the building envelope and its air tightness) and T_{out} is the average outdoor temperature for a specific day. When h_{demand} is a negative value, it represents the heating demand for that specific day (if positive there is no need for heating). Based on this method, the specific annual heating demand is about 11 kWh/m^{2}a. Figure 2 shows the resulting heating demand during the year.

The *degree days* are used to calculate the daily cooling demand during the summer months of June, July and August. During these months no heating demand is calculated as no extreme low temperature is expected. The minimum outside temperature to start the cooling system was set to 15°C. The difference between 15°C and the average outside temperature during the summer (eKlima, 2010) is ΔT = (T_{out} - 15°C) = 2.7°C. Assuming the standard energy demand for cooling a commercial building in Norway equals to 4 kWh/m^{2}a (Grini et al., 2009), which takes into account the internal heat gains due to equipment and occupants, then the average power needed for cooling the building is $P_{cool,average}$ = 1.6 kW. If we divide this power by ΔT we obtain the specific cooling loss rate ($P_{cool,specific}$), which represents the amount of power needed to keep a comfortable office temperature per Celsius degree above 15°C outdoor temperature:

$$P_{cool,specific} = \frac{P_{cool,average}}{\Delta T} = 0.60 \frac{kW}{^{\circ}C} \tag{2}$$

This parameter is used to calculate the daily variation of power demand for space cooling depending on the outside temperature. Figure 3 shows the resulting cooling demand during summer.

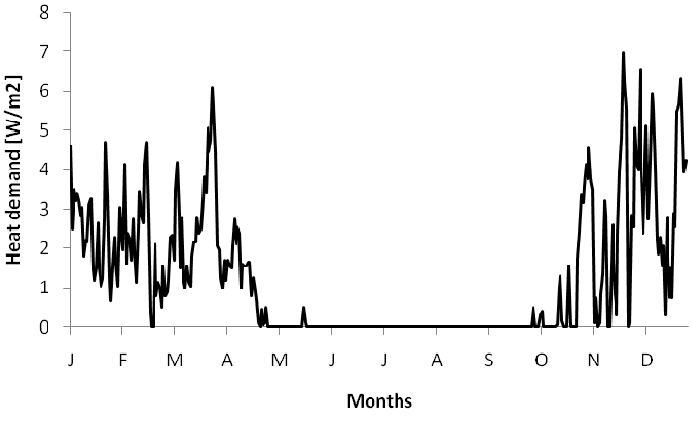

Fig. 2: Annual evolution of the estimated heat demand of the analysed building. Given are daily averages.

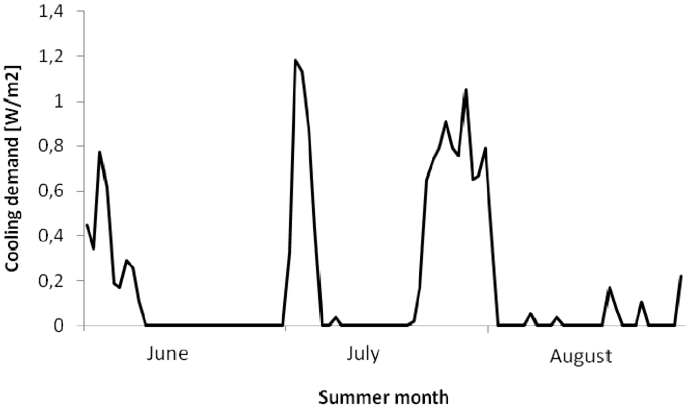

Fig. 3: Estimated cooling demand during summer. Given are daily averages.

The average electricity consumption of the RES building during the year is about 420 kWh/day. We consider a base load profile during weekends and holidays (no lighting and equipment load, except for the data server, which needs to be continuously operated). The specific load will be about 44 kWh/m^2 per year, lower than class A energy label for buildings (<84 kWh/m^{2}a (Norges vassdrags og energidirektorat, 2010)). Figure 4 shows the share of different energy loads during the seasons.

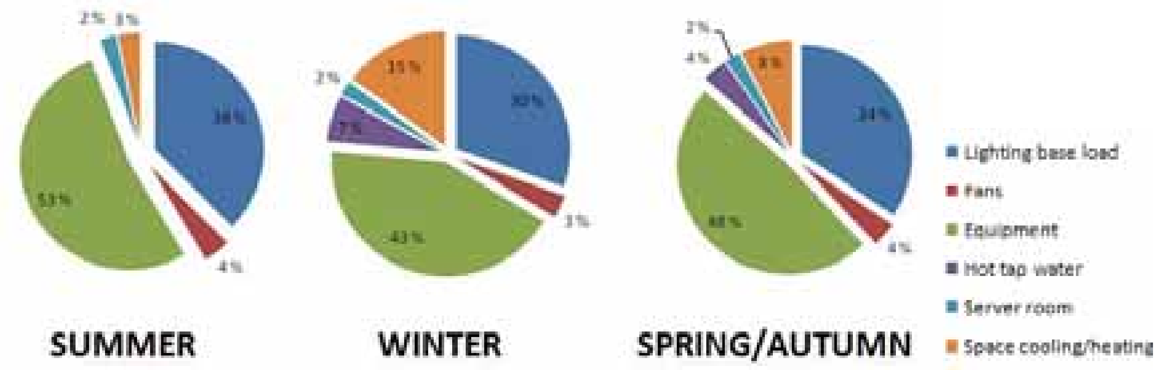

Fig. 4: Share of different energy loads during the seasons. Space cooling demand occurs only in summer.

3.2. Resource assessment

The resource assessment was performed by comparing publically available data sources.

For the specific solar radiation on a horizontal surface, the databases from NASA (NASA, 2010) and the Photovoltaic Geographical Information System of the European Commission Joint Research Centre, PVGIS (PVGIS, 2010) were consulted. For the location of Bjerkreim the average of both sources gives a value of 897 kWh/m^2 per year. For an optimal inclined plane (inclination of 58.6°) the corresponding irradiation value is 1053 kWh/m^2 per year.

For wind speed data, results from the Weather Research and Forecasting Model (WRF Model, 2010) were selected as the most reliable public data source available. The average wind speed in Bjerkreim (5.5 - 10.4 m/s monthly averages at 50 m above ground) was found to follow a typical Northern European trend: lower wind speeds in summer and higher in winter. The combination of solar and wind power is therefore beneficial for a hybrid system, since the two sources compensate for each other's minima.

3.3. Modeling and Optimization of the Hybrid System

The hybrid system simulation was carried out by using the software HOMER, and several hybrid system scenarios were tested. The scenarios differ in terms of the number and size of wind turbines, the PV module area and the use of the grid. The case of a grid-connected system is then compared to a stand-alone system (with the addition of a battery bank and a biogas generator), to check the economic cost of going off-grid for a commercial building.

In the grid-connected case, the hybrid system is composed of:

- Wind turbine: three types of wind turbines (WT) will be investigated (Northern Power NV100/19 (NPWT, 2010), Entegrity eW15 (eW15, 2010) and BWC- Excel S (BWC, 2010)). The rated powers are 100, 50 and 10 kW, respectively, and 1 or 2 wind turbines of the same type will be simulated.
- PV modules: Sanyo HIT Power 215N solar modules (Sanyo, 2010) are assumed. The simulation will be run with 25, 50 and 75 kWp PV power. The effect of temperature is considered in the simulation.
- Converter: the size of the converter will be equal to the PV size (as the wind turbine already produces alternating current). Therefore the choice of the converter will be 25, 50 or 75 kW, according to the PV system size.
- Grid: the electricity cost from the mains is set as 0.1 €/kWh and the sellback rate is assumed at 0.01 €/kWh (Haase and Novakovic, 2010). This feed-in tariff is currently only valid for wind power. We will assume this tariff for all excess energy produced by the hybrid system, otherwise a dump load would be necessary to dissipate excess energy produced by the PV system. Net metering is applied.

For the stand-alone case, a battery bank and a biogas backup generator are added to the system and the converter has different size options:

- Battery bank of the type Hoppecke 8 OPzS 800. Nominal voltage 2 V, Nominal capacity 800 Ah, lifetime throughput 2741 kWh, 24 batteries per string, 1 or 2 strings.
- Biogas backup generator: Stratos TBG 90, calorific value of the biogas 23 MJ/m^3, nominal electrical power output 91 kW (Biogas generator, 2010). Generation in part load 45, 50, 60, 65 or 70 kW.
- Converter: for each scenario, the size of the converter will be equal at least to the PV array size up to the maximum power of the wind turbine (to allow battery charging). Therefore the size will be 25, 50, 75, 100 or 200 kW.

In the grid connected case, the renewable energy fraction RF [%] during the year is calculated as:

$$RF = \frac{WT\ Output + PV\ Output - Energy\ Sold\ to\ Grid}{AC\ Load} \cdot 100, \qquad (3)$$

where all the terms are expressed in [kWh]. The RF is in this case an index of renewable energy produced and used directly on site. In the stand-alone case the renewable fraction does not include the term '*Energy Sold to Grid*', and the energy from the biogas is subtracted since the biogas is assumed to be not produced on site.

Tab.1 shows the characteristics of the different simulated scenarios (six in total). Fig.5 gives an overview of the calculated energy flows, as well as the RF value for the grid-connected case with a 50 kW wind turbine. The RF increases significantly when increasing the number of wind turbines from 1 to 2 (from Scenario 1' to Scenario 4' the increase is 9 %).

If we choose to compare the use of 25 kW of PV power to 50 kW (*i.e.* Scenario 1' and 2'), RF increases by 8 % but this also means that the roof area dedicated to the PV module will be twice as large. It can also be observed that most of the renewable energy produced is sold to the grid. The reason is found in the temporal mismatch between the energy generation and the building load.

Tab.2 presents the optimal results for each wind turbine case in the stand-alone simulations. The excess energy produced is high and cannot be used by the system, therefore a dump load may be required. For the same purpose, the system control management can imply droop control by the inverter, as well as a smart control of the PV and wind turbine production. The biogas consumption is significant: the transport of biogas from the production site to the user has to be studied carefully, as there is no public gas distribution network available. An onsite gasometer and truck transport should be carefully planned. The RF term is quite high even if it does not include the biogas energy.

Table 1: PV size and wind turbine number in the simulated scenarios.

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
PV [kW]	25	50	75	25	50	75
WT [#]	1	1	1	2	2	2

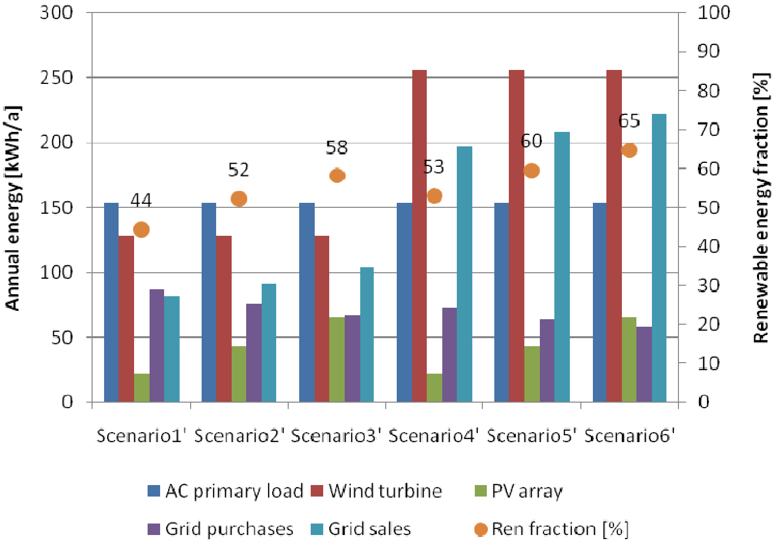

Fig.5: Overview of the annual energy (kWh/a, left axis) and the renewable fraction (%, right axis) produced in the six different scenarios with the Entegrity wind turbine.

Table 2: Optimal results for each wind turbine case for stand-alone simulations.

WT type and size	PV [kW]	RF [%]	Excess energy [MWh/a]	Biogas [m^3/a]
BWC 10 kW	75	48	24	44430
BWC 20 kW	50	47	28	46563
Entegrity 50 kW	25	69	98	37451
Entegrity 100 kW	25	84	234	29541
NP 100 kW	25	80	175	30935
NP 200 kW	25	90	407	25866

4. Data analysis

4.1. Validation of results as estimated by the HOMER scheme

The results of simulation programs should ideally be checked against measured values or compared with other simulation programs. When this is not possible, other parameters can help to validate the simulation results. The latter approach is taken here.

For the PV system, the annual power yield is expected to be in the range 700-1000 kWh/kWp (German Energy Society, 2008). HOMER provides a value of 863 kWh/kWp per year for the current simulation (the total solar irradiation on the module plane is given as 1053 kWh/m^2 per year). This value may be compared to values reported from well-designed systems in Germany reaching close to 1000 kWh/m^2, where the total annual irradiation is about 15 % higher (Drews et al., 2008).

A suitable parameter for checking the simulated wind turbine performance is the capacity factor (the mean output divided by the total rated capacity). Capacity factors typically scatter between 15 and 40 % depending on location and turbine design. In our case study, HOMER produces capacity factors of 20 % (BWC- Excel S), 27.7 % (Entegrity eW15) and 29.3 % (Northern Power NV100/19). These values can be considered reasonable for turbines with the given ratios of rated power per rotor area as selected here, and for the given wind conditions.

4.2. Economical Study and Discussion of Results

HOMER ranks the simulation results by means of the total Net Present Cost (NPC). Costs include capital costs, replacement costs, operation and maintenance costs, fuel costs, and the cost of buying power from the grid. Revenues include salvage value and grid sales revenue. The cost of energy (COE), in €/kWh, is also provided for each simulation. Fig. 6 and 7 show an economic overview of the simulated scenarios. The main objective is to find out which scenarios have a high renewable fraction with low NPC and COE. Another criterion to evaluate is the degree of independence from the grid.

In the grid-connected case, the range of NPC varies from 400 k€ to 1700 k€ and the COE varies from 0.2 to 0.89 €/kWh. By observing Scenarios 2’ and 3’’ it can be seen that with nearly the same NPC, the RF of 3’’ is 10 % smaller. The choice would therefore fall on Scenario 2’.

In the stand-alone case, the NPC is much higher, varying from 1000 to 1800 k€ and the COE from 0.5 to 0.9 €/kWh. It can be seen how the RF changes from Scenario 4’ to 3’’: the NPC slightly decreases but the RF is over 30 % smaller. The stand-alone hybrid system has a too high cost to justify an investment. Moreover, the national grid is not located far from the building site. Therefore, the best choice under these conditions would be a grid-connected hybrid system.

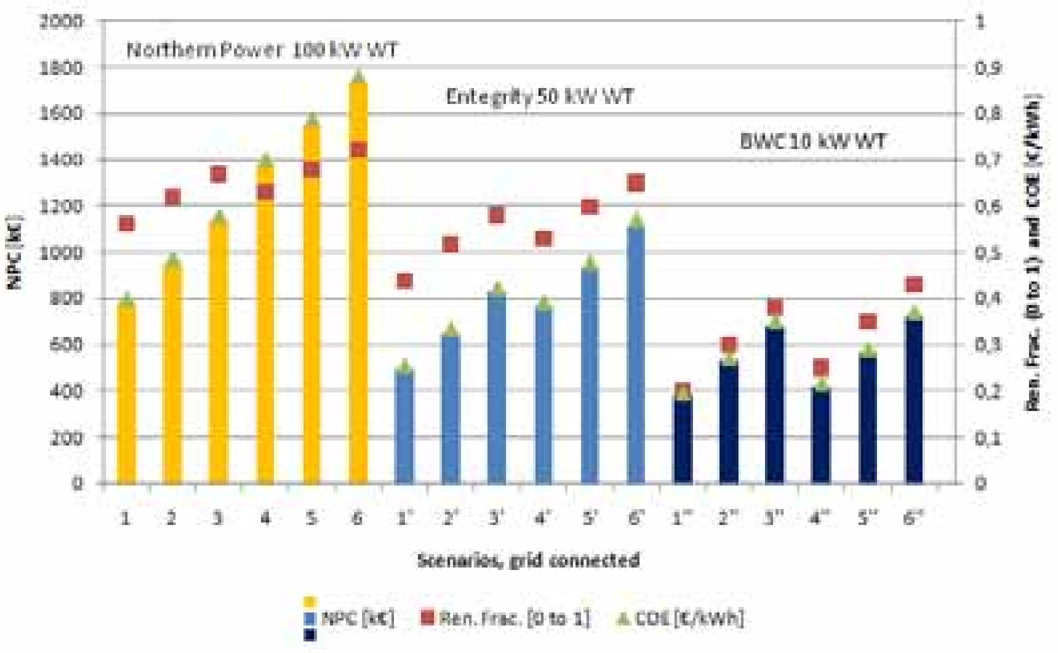

Fig. 6: Economic overview of the grid-connected scenarios. Given are net present cost, renewable fraction and cost of energy for the different configurations analysed.

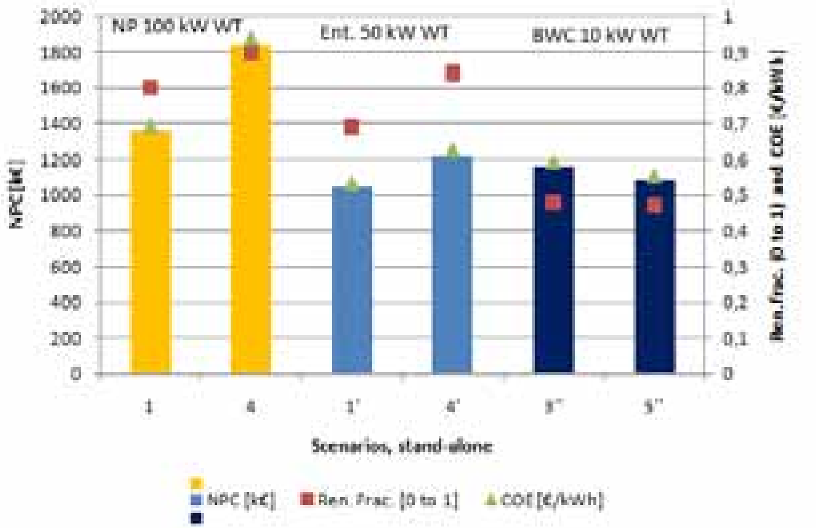

Fig. 7: Economic overview of the stand-alone scenarios. Given are net present cost, renewable fraction and cost of energy for the different configurations analysed.

5. Conclusions

It is clear that a renewable energy hybrid system - even for the less expensive grid-connected option - is an expensive and not competitive investment under the given economic conditions in Norway. However, other values have to be taken into account when making an overall evaluation: the development of research on alternative energy sources in view of fossil fuel shortage, the future lower cost of components (more available in the market and better designed), the continuous increase of efficiency (for instance in inverters and batteries), and the possible use of excess renewable energy for charging electric cars. Moreover, the choice of using a renewable energy hybrid system will have a positive environmental impact, and contributes to meet the objectives of the EU growth strategy for the coming decade in terms of reduced CO_2 emissions and increased production from renewable energy sources (EU 2020).

The high NPC of the systems is due to the current lack of incentives for developing new renewable energy systems. Norway, due to large share of hydropower in the grid, has striven to adopt effective feed-in tariffs that could facilitate renewable energy investments. There are several barriers to the construction of low-emission zero-energy buildings. As with many energy-efficient technologies, initial costs are high and building owners may perceive the long-term benefits as uncertain if the initial investment is not reflected in re-sale values. However, in the near future, new building codes in Norway will demand an energy fraction of between 50 % and 60 % to be covered by renewable energy sources. Moreover, a green certificate market will start in 2012 to promote renewable energy installations, and this is expected to have a positive influence also on the market for low-emission buildings.

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