TECHNO-ECONOMIC OPTIMIZATION OF A SUSTAINABLE ENERGY SYSTEM FOR A 100% RENEWABLES SMART HOUSE

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ABSTRACT: The continuous increasing negative effects of fossil fuel consumption on society and the environment, opens a major interest into environmentally friendly alternatives to sustain the increasing demand for energy services. Despite the obvious advantages of renewable energy, it presents important technical and economic challenges. One such challenge is the discontinuity, or intermittency, of generation, as most renewable energy resources depend on the climate, which is why their use requires complex design, planning and control optimization strategies. This paper presents a model and optimization for a sustainable energy system for a 100% renewables based Smart House (SH). We have devised and analysed an innovative high-efficiency approach to residential energy supply. The analysis involves detailed technical specifications and considerations for providing optimal supply of electricity, heating, cooling, and hot tap water demand, balancing fluctuating wind power and both solar power and solar thermal supply utilizing advanced heat pump and both electro-chemical electricity storage, and hot and cold thermal storages. Our research is basically concerned with the question of how to design 100 % renewable based energy supply systems. Our results show this is indeed both possible and relatively feasible.

1. INTRODUCTION

The continuous increasing of negative effects of fossil fuel combustion on the environment, also in addition to limited stock of fossil fuel, opens a major interest into and change to environmentally friendly alternatives that are renewable to sustain the increasing energy demand [1]. Despite the obvious advantages of renewable energy, it presents important drawbacks due to the discontinuity of generation, as most renewable energy resources depend on the local climate, which is why their use requires complex design, planning and control optimization methods. Due to the continuous advances in computer hardware and software are allowing researchers to deal with these optimization problems using computational resources, as can be seen in the large number of optimization methods that have been applied to the renewable and sustainable energy field [2]. In most countries, buildings account for a substantial part of the energy supply. Therefore, the development of sustainable buildings plays an important role in the transformation of national energy systems into future sustainable energy supplies aiming at reductions in fossil fuels and CO2 emissions. The design and perspective of sustainable buildings have been analysed and described in many recent papers including concepts like net zero emission buildings and plus energy houses [3]. Different authors have made calculations and economic analysis for large and small scales renewable energies technologies as: identification of the most promising markets in Europe for the installation of solar combi plus systems [4], technology analyses to facilitate the integration of fluctuating renewable energy sources [5], analysis for 100% renewable energy systems [6], role of the heat pump in future energy systems [7]. Also the importance of using natural refrigerants in the actual and future energy systems is presented in reference [8].

In this paper the model and optimization of a renewable energy system for a Smart House (SH) in Denmark is presented. The calculation comprises technical requirements and potentials for an optimal design of electric consumer, heating, cooling, and hot tap water production techniques, also balancing fluctuating wind and solar power. The research about long-term solutions concerns the question if the energy supply system designed is capable of covering the demands for the SH now and in the future. The sketch of the sustainable energy system is presented, the main components characteristics followed by simulation results and conclusion.

2. DESCRIPTION AND MAIN COMPONENTS OF SMART HOUSE ENERGY SYSTEM

The energy system for the SH is divided in three main areas as follows: SH energy demands, storage and process. Figure 1 illustrates a sketch of the energy system functioning for the SH.

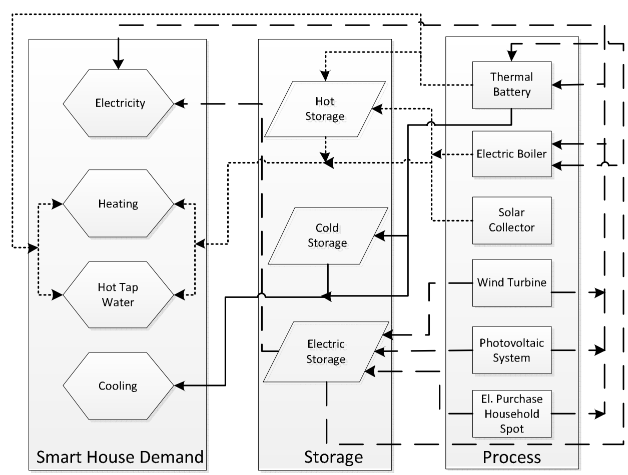

Figure 1. Sketch of energy system functioning for SH.

The building is energetically efficient; all the energy sources are renewable and connected to the building forming a Smart Grid (SG) as illustrated in Figure 2. The SH is considered to be situated in Denmark and all the data and profiles for hourly consumption used for simulation are according to Danish policies. As it can be seen in the figure above the SH demands it contains the electricity, heating, hot tap water (HTW), and cooling. All this demands are supplied by the processes which are: water source heat pump (WSHP), electric boiler (EB), solar collectors (SC), wind turbine (WT), photovoltaic system (PVS), and the electric purchase household spot (EPHS) from the national energy system. The storage plays an important role of balancing the energy demand with the processes. More detailed description for all the components of processes and storages of the system can be seen in Table 1.

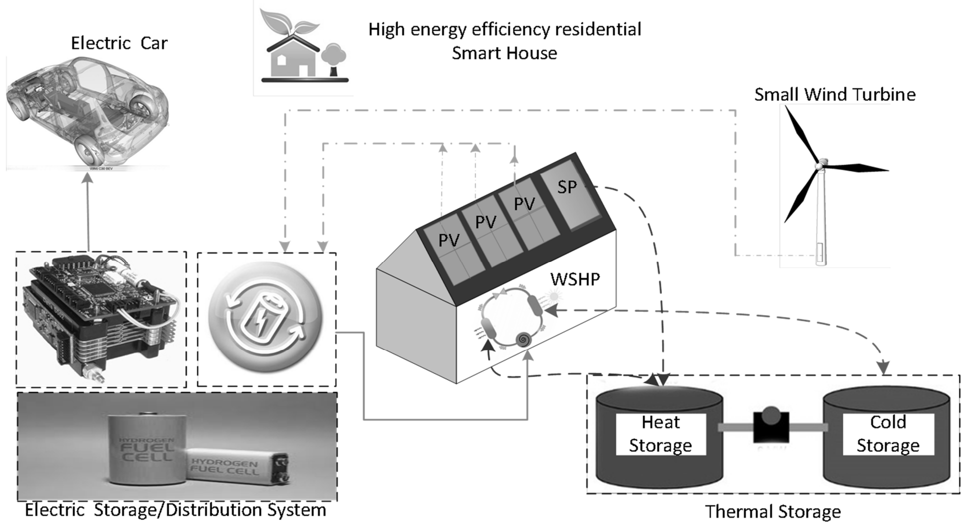

Figure 2. Smart Grid principle sketch of SH sustainable energy system.

Table 1. Process and Storage description for the SH.

Process	Technical data	Capacity
Water source heat pump operated in simultaneous heating and cooling production mode	- 2 stage scroll compressor - refrigerant CO_2 (R744) - water-water	4.5 kW
Electric boiler	- no. of elements: 2 - element size: 3000W	6 kW
Solar collector	- flat plate collectors	7 kW
Wind turbine	- permanent magnet synchronous generator	11 kW
Photovoltaic system	- Peak efficiency 97.5% - CEC efficiency 97.0%	6 kW
Storage	**Technical data**	**Capacity**
Hot water storage	- two internal HEX coils - max temperature 95ºC - ΔT is 50ºC - utilisation 90%	1000 l
Cold storage	- ΔT is 12ºC - utilisation 90%	1000 l
Electric energy storage	- Li-Ion battery	24 kWh

The demand specifications of the SH used for simulation can be found in Table 2.

Table 2. Design specification and demands for the SH. Hourly distribution according to Figs. 3-6.

SH demand	Demand/Year [kWh/m^{2}Year]
Heating demand and domestic hot water	85
Cooling demand	20
Electricity demand end-use, no process	40

Electricity demands for end-use and for processes are provided by the WT, PVS, electric storage and EPHS at the end if needed for balancing the electric energy consumption. All the SH consumers and processes who need electrical energy (WSHP, EB) will use the energy from the processes which provide it, than from electrical storage and as a last option from EPHS. The electrical energy surplus (after filling the storages) can also be sold and reducing the costs giving back the energy used from EPHS, or even makes profit.

The WSHP is used conversion technology for providing building thermal energy services; cooling, heating, and water heating like air and ground sources heat pump [9]. WSHP is also a good option for increasing energy efficiency, producing heat or cold from the electrical energy supplied by a small WT, as in reference [10], and PV when electricity is not used for SH electricity demand. Flexibility for such a system plays a key role for optimizing, increasing its efficiency, and reducing the costs.
The hourly energy demand profiles for one year used for calculation are shown in Figure 3 for space heating, Figure 4 for HTW, and Figure 5 for space cooling. Electric end-use demand profile, without processes included is illustrated in Figure 6. The SH is well-insulated, fully equipped with all automation and high tech technologies and it has a surface of 130m^2. As reference house (RH) model for the simulation an average house of 130m^2, using EPHS for electricity demand, gasoil boiler for heating and HTW, and air conditioning unit for cooling was chosen.

The analysis is performed using the COMPOSE software that combines detailed operational simulation under the deterministic techno-economic constraints of the SH and the existing appliances with a least-cost marginal-dispatch model for the energy system in which the SH is analysed. The energy system model allows for an identification of the marginal system-wide consequences with respect to the intermittency-friendliness of operation and CO2 emissions [7]. These particular system analysis methodologies are described in further detail below.

In COMPOSE, the user defines an energy option in terms of end-use requirements, storages, and conversion processes (e.g. heat pump). Options may be designed from scratch or based on build-in libraries. Furthermore, the user defines an energy system in terms of spot markets, candidate marginal power producers, electricity demands, and intermittent production.

For both option and system, parameters are specified on an hourly basis for each year of analysis. System specific parameters may be imported from utility databases, or adapted from COMPOSE's build-in libraries [11].

COMPOSE then identifies the option's optimal operational strategy by mixed-integer linear programming under the objective function of minimizing the economic cost of meeting heating and cooling demands for the period of simulation under given techno-economic constraints and boundaries, including hourly values for end-use requirements, capacities and efficiencies, market prices, variable O&M costs. The resulting detailed energy balance includes e.g. fuel and electricity consumption, storage states, energy losses, energy costs. For the SH, based on the identified least-cost operational strategy, COMPOSE uses the resulting net electricity profile – the Smart House's hourly electricity consumption profile - as a basis for calculating the resulting energy system impacts, including system-wide primary energy consumption and system-wide marginal CO_2 emissions [12].

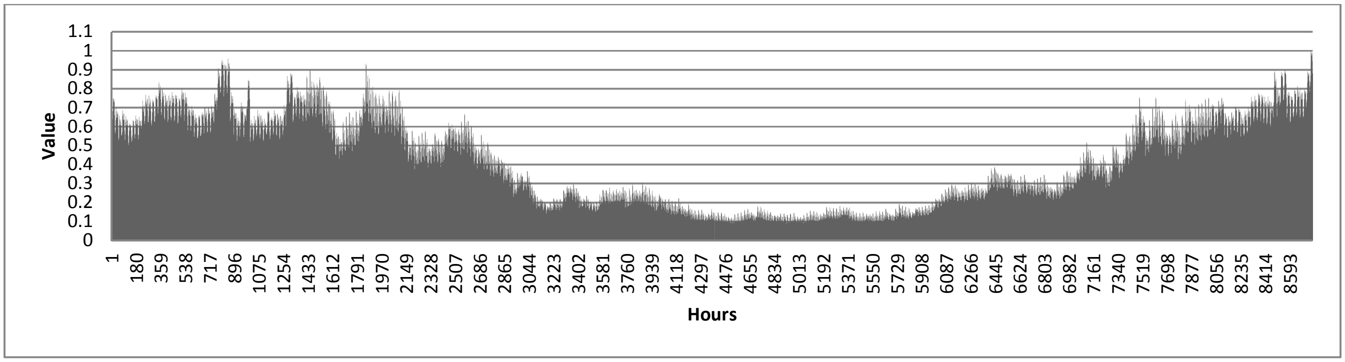

Figure 3. Space heating demand profile.

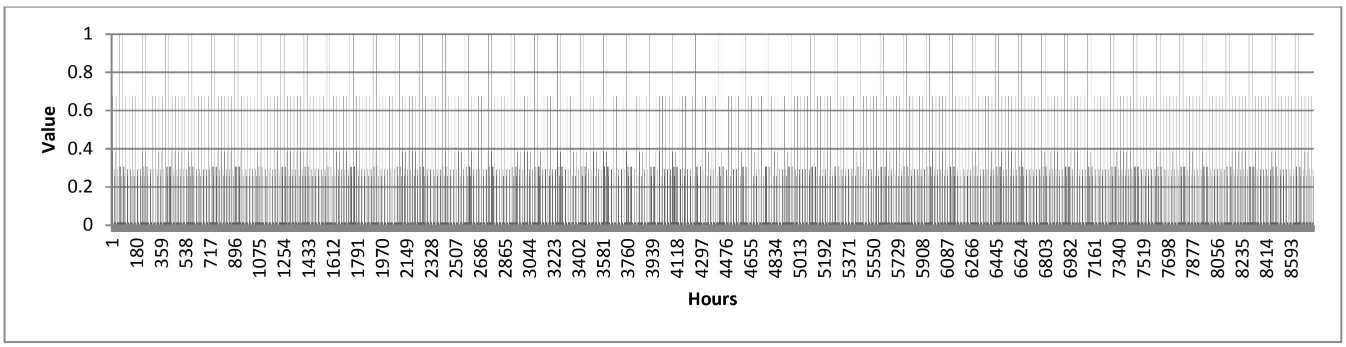

Figure 4. HTW demand profile.

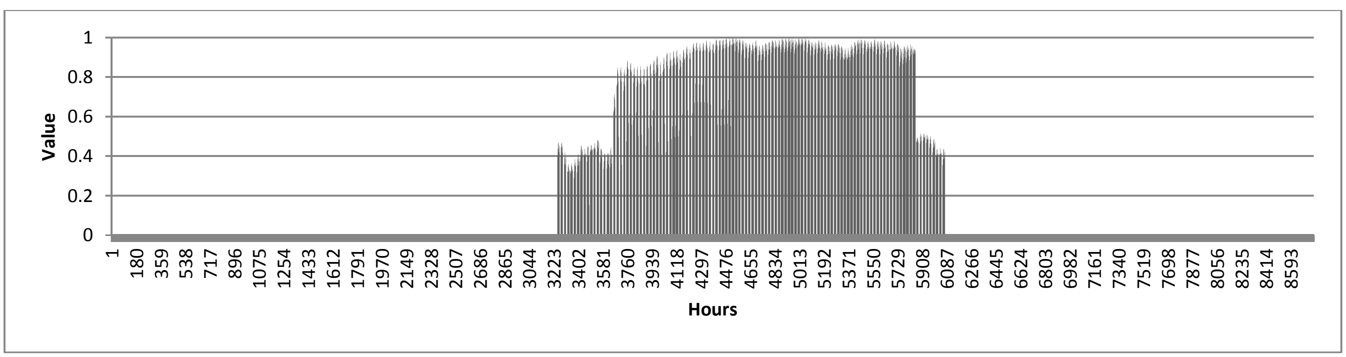

Figure 5. Space Cooling demand profile.

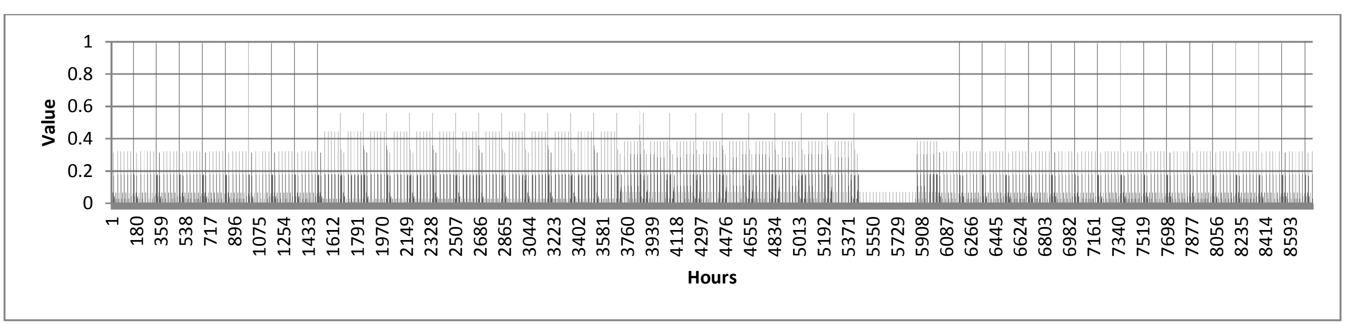

Figure 6. Electric end-use demand profile, without processes included.

3. RESULTS AND DISCUSSION

The assumptions for the simulation where presented in the description and the main components of the energy system for the SH.

The main objective of the analysis was to find the optimum option between the demand, processes and storage for a sustainable SH energy system. In this paper the heating, HTW, cooling, and electricity demands, storage and processes for the SH are discussed and energy analysis is presented.

Figure 7 illustrates the heating (includes space heating and HTW demands) which it is modelled in the West Denmark energy system according to 2011 statistics, and cooling demands, processes and storages of the SH for a period of 24 hours in June.

It can be seen in the chart from Figure 7 that during the night when the heating is needed the cold storage will fill up and will be used during the day when the outside temperature starts to increase and the cooling demand will increase. When the cold storage cannot fill the demand for cooling the (TB) WSHP will take control and will ensure that the cooling demand is covered during the day. The production of electric boiler is zero in this case because the demand of hot water is not that big, like in winter period, and the other processes can cover the need. During the day the produced heat from the SC The production of heat during the day made by (TB) WSHP and SC will be stored if not needed and used in the night.

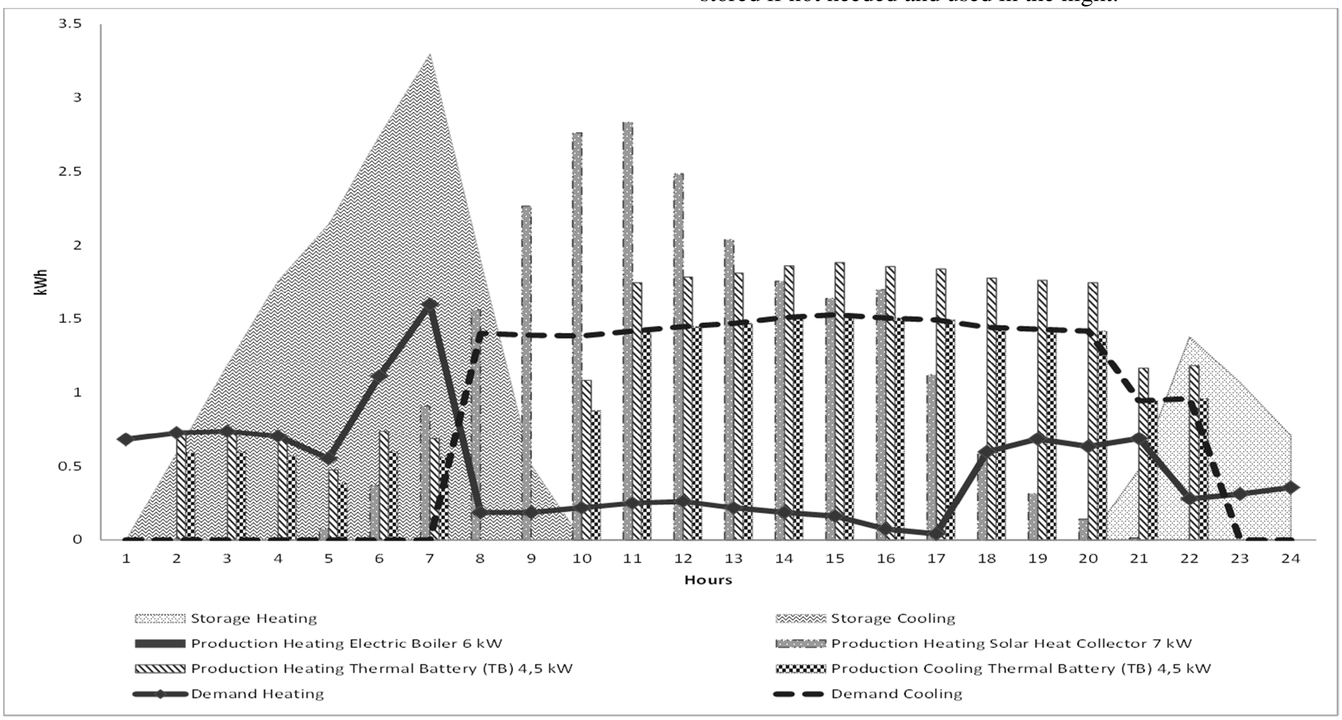

Figure 7. Overall chart of demands for space heating, cooling, processes, thermal storage content for a selected 24 hours period.

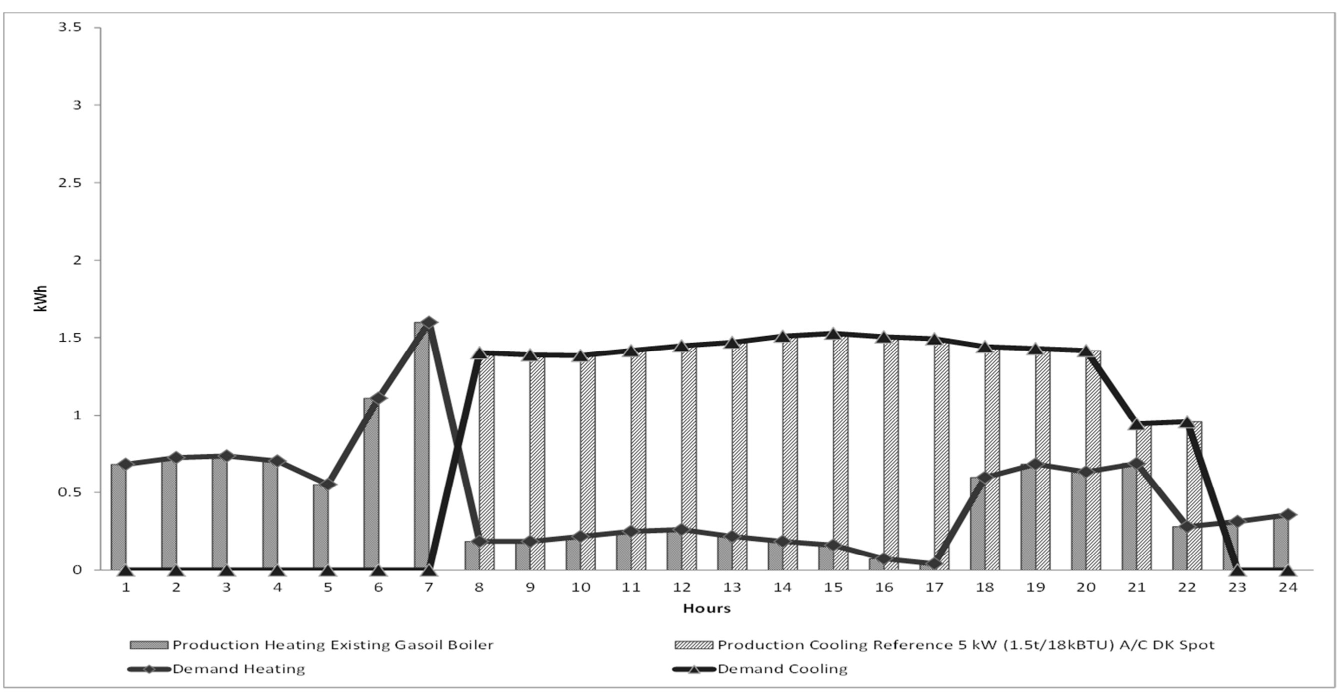

Figure 8. Overall chart of demands for space heating, cooling and processes for the RH, 24 hours period.

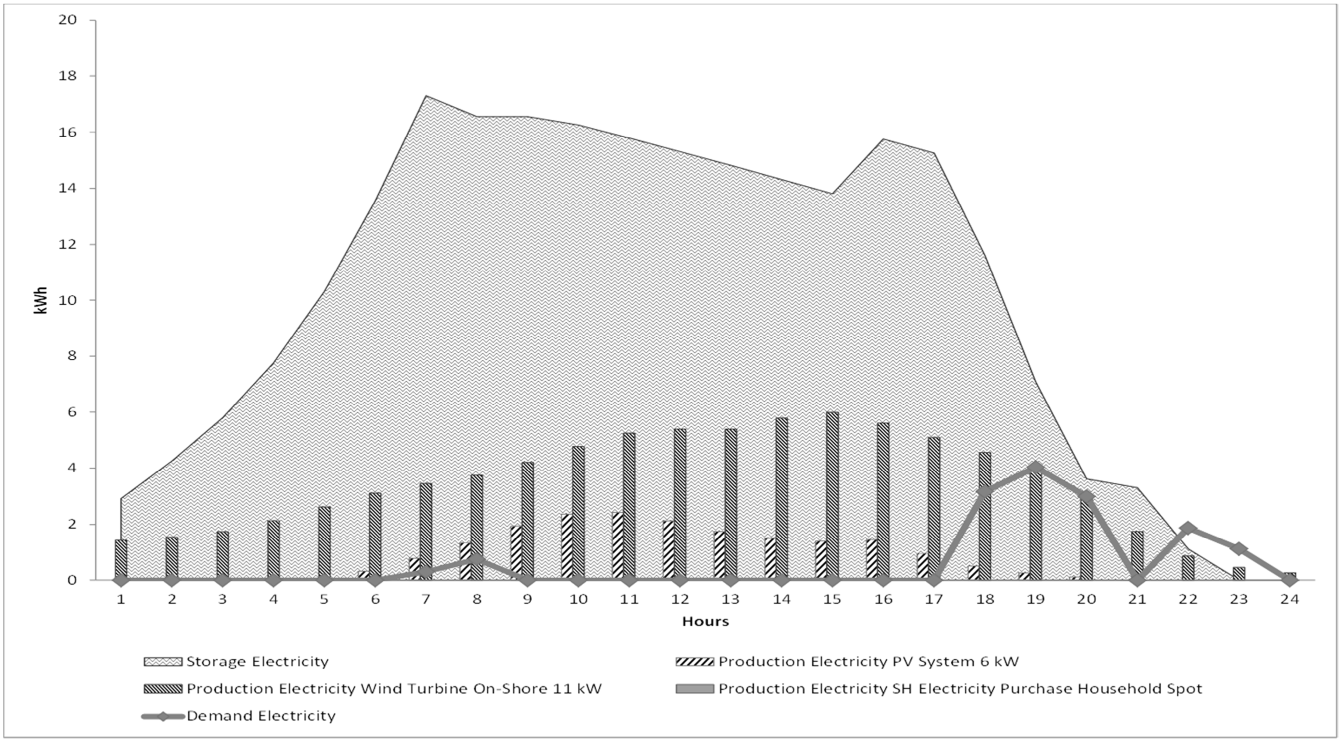

Figure 9. Electricity demand, production from processes for the SH, 24 hours period.

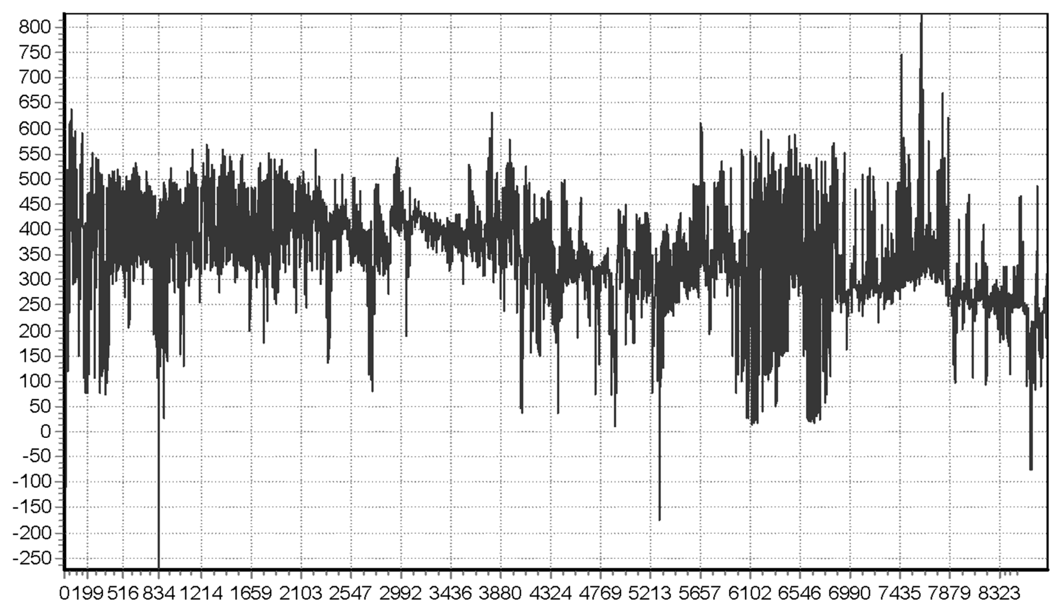

Figure 10. Denmark West Spot 2011

Figure 8 illustrates the heating and cooling demands covered by processes which provide the energy needed by the RH. The chart is for the same period as for SH. All the demands are covered by the processes which use energy from the EPHS. The demand and electricity production from EPHS are illustrated in Figure 10, Denmark West Spot 2011 statistics. Figure 9 illustrates the end-use electricity demand, storage option and processes for the SH. The electricity demand is fully covered by the processes for this period of 24 hours not needed to buy any electricity from EPHS. In Figure 9 the end-use demand of electricity is presented but the processes and the storage cover all the electricity needs for that period including the processes which need it, as: WSHP, EB. This analysis shows how the processes and the storages deal with the demand and for the SH reducing the costs and increasing the comfort. It is shown in the analysis that the SH can be energetically independent comparing with the RH which uses all the energy from the EPHS.

Figure 11 illustrates the comparative system-wide fossil fuel consumption of the RH and the SH. It appears, that while the RH results in an annual primary fuel consumption of 28.4 MWh, then the SH results in a negative annual primary fuel consumption of -49,0 MWh due to the replace fossil fuel consumption in central electricity generation. Figure 12 illustrates the associated system wide CO_2 emissions for SH and RH. The SH has consequently negative CO_2 emissions amounting to 15 ton per year, while the RH emits 8 ton per year.

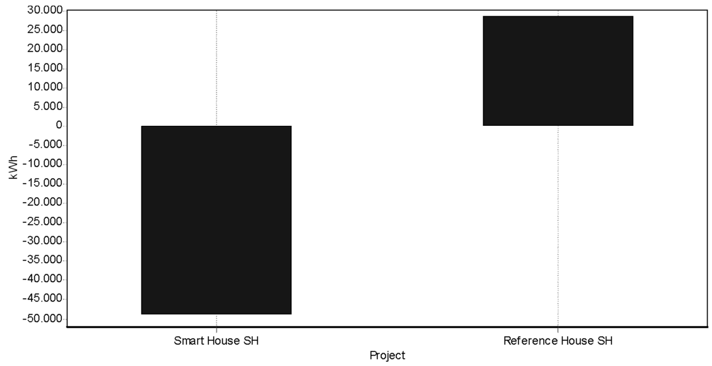

Figure 11. System wide primary energy consumption for SH and RH.

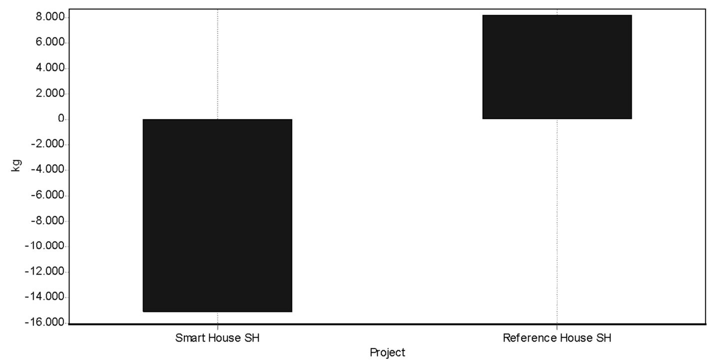

Figure 12. System wide CO_2 production for SH and RH.

4. CONCLUSION

In this paper an optimization calculation for sustainable energy system for a SH situated in Denmark was presented. System functioning model and assumptions used for the calculation were presented and simulation results for space heating, cooling demands, HTW, and electric demands. How storages and how processes operate for an optimum balance between demand and storing energy reducing the costs for purchasing energy significantly. The presented results are presented for a 24 hours period in July for better understanding and ease of chart reading, even if the demand hourly profiles and the simulation where made for a period of a year. As future work a techno-economic optimization for the sustainable energy system of the SH is considered to search the optimum option for an independent energy system.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. R. Saidur, M.R. Islam, N.A. Rahim, K.H. Solangi, A review on global wind energy policy, *Renewable and Sustainable Energy Reviews*, Vol.14, pp. 1744–1762, (2010).
2. R. Banos, F. Manzano-Agugliaro, F.G. Montoya, C. Gil, A. Alcayde, J. Gomez, Optimization methods applied to renewable and sustainable energy: A review, *Renewable and Sustainable Energy Reviews*, Vol.15, pp. 1753–1766, (2011).
3. H. Lund, International Congress E-nova, *The Role of Sustainable Buildings in 100% Renewable Energy Systems*, band 14, pp. 1-9, (2010).
4. J. Rodriguez, R. Fedrizzi, Description and Visual Representation of Most Promising Markets, *EURAC Research*, Bolzano (2010).
5. M. B. Blarke., Towards an intermittency-friendly energy system: Comparing electric boilers and heat pumps in distributed cogeneration. *Journal Article (reviewed). Applied Energy*, Vol. 91, Issue 1, March 2012
6. H. Lund, B.V. Mathiesen, Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050, *Energy*, Vol.34, pp. 524–531, (2009).
7. M. B. Blarke, K. Yazawa, A. Shakouri, C. Carmo, Thermal battery with CO2 compression heat pump: Techno-economic optimization of a high-efficiency Smart Grid option for buildings, *Energy and Buildings*, Vol. 50, pp. 128–138, (2012).
8. G. Lorentzen, The use of natural refrigerants: a complete solution to the CFC/HCFC predicament, *Int. Journal of Refrigeration*, Vol. 18, No. 3, pp. 190–197, (1995).
9. V. S. Craciun, C. Bojesen, M. B. Blarke, V. Trifa, A flexible and low cost experimental stand for air source heat pump for Smart Buildings, IEEE Conference proceedings, pp. 1040-1045, (2012)
10. V. S. Craciun, K. Park, H. Sun, V. Trifa, Modelling of a permanent magnet synchronous generator wind energy conversion system for a Smart Building, S*cientific bulletin AGIR*, ISSN-L 1224-7928, Online: ISSN 2247-3548, Vol. 4, pp. 149–154, (2012).
11. M.B. Blarke, H. Lund, The effectiveness of storage and relocation options in renewable energy systems, *Renewable Energy*, Vol. 33, pp. 1499–1507, (2008).
12. M.B. Blarke, COMPOSE http://energyinteractive.net, 2011.