Rooftop photovoltaic (PV) systems for industrial halls — achieving economic benefit through lowering energy demand

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Abstract: Industrial halls are characterized with their relatively high roof-to-floor ratio, which facilitates ready deployment of renewable energy generation, such as photovoltaic (PV) systems, on the rooftop. To promote deployment of renewable energy generation, feed-in tariff (FIT) higher than the electricity rate is available in many countries to subsidize the capital investment. FIT comes in different forms. If net FIT is the case, in order to maximize the economic benefit, surplus electricity generation that exports at the higher FIT at each of the hour is desirable.

One way to achieve surplus electricity generation is by increasing generation capacity, which unfortunately is synonymous to higher capital investment. Instead of increasing generation capacity, surplus electricity generation can also be achieved by lowering the energy demand of the building. That is particularly the case for industrial halls, which are usually subject to high energy demand for space conditioning in order to remove the excess heat gain due to the many power-intensive manufacturing processes.

Building energy performance simulation tools can be used to explore the different building design options that could lower the energy demand. In this paper, single-objective optimization on investment return will be deployed to study the cost effectiveness among different options in lowering energy demand. The idea will be demonstrated with a case study of a warehouse.

Keywords: industrial halls, photovoltaic, PV systems, cost-benefit analysis, energy performance simulation, optimization, energy demand, renewable energy generation

1. Introduction

In the last decade, global warming, due to emissions from fossil fuel based energy generation, has become a concern. Electricity generation in 2008 from renewable energy sources is estimated at 16.7% in Europe (Eurostat, 2011a), and 18.7% around the globe (IEA, 2010). In 2007, the EU-wide directive (EU, 2011a) was set such that power from renewable energy sources shall comprise at least 20% of total energy generation by

2020 for the European Union as a whole. Each country has also set a target, for example, 17% for Italy, which is more than triple of the 2005 percentage of around 5% (REN, 2010).

The industrial sector is one of the heaviest consumers of energy. In Europe, this sector consumed 24% of the total energy consumption in 2009 (Eurostat, 2011b), while in the United States, the sector consumed 32% in 2009 (LLNL, 2010). Some of the energy from this amount was consumed in the manufacturing processes and for lighting, while much of the rest was spent to provide space conditioning to maintain the building within a reasonable or legally allowable temperature range. Since the manufacturing processes generate large amount of heat as a by-product, buildings in general require cooling to remove the excess heat gain.

Industrial halls are characterized with their relatively high roof-to-floor ratio as compared to other types of buildings of similar total floor area. This makes it quite beneficial to incorporate renewable energy producing components into the building design by taking advantage of the proportionally large rooftop area, which in most cases does not serve any particular purpose. Photovoltaic (PV) systems were posed as a promising technology to produce renewable energy. PV systems could be readily deployed and attached to the rooftop with no special requirement on or alteration to the building design. In addition, industrial halls are mainly situated in sparsely populated areas with open fields in which the performance of PV systems is not hampered by shading of surrounding buildings. Therefore, grid-connected solar PV systems could be one of the options.

However, at the current price level, deployment of PV systems is synonymous with high capital investment, which is not likely to be covered by savings in electricity cost at the current electricity rate. In order to promote wider deployment of PV systems in the hope that wider adoption will lower the cost of deployment in the future, government policies come in different forms of economic incentives to compensate the high investment cost. Out of these, feed-in tariff (FIT) is the most common form of such incentives (EEG, 2007).

The evaluation of the economic benefit requires the consideration of the different feed-in tariff schemes and the various economic parameters, such as electricity rate, discount rate, and others; which are the result of market forces rather than factors that the building stakeholders have control of. On the other hand, the building stakeholders could play a more active role in the design of the buildings. With better building design, energy consumption will decrease. As a result, electricity generation shall satisfy the lowered consumption for more hours such that a smaller-capacity PV system will still be economically viable (or a larger-capacity PV system will yield higher benefit). Lee et al. (2011) presented the cost-benefit analysis under such premise.

Current design practice in evaluating the capability of PV systems in meeting a building's energy consumption is to assume the same daily consumption load profile for the whole year or to adopt an annual total consumption (CEC, 2001). Little of the literature studying the performance of PV systems actually conducts an hourly assessment on matching the generation to the demand profile.

To fill the gap, this paper will assess the economic performance of PV systems based on computational simulation of both the energy generation capability of the PV system and the energy consumption of the industrial hall building. A notable portion of the energy consumption, that is the cooling load of the building, is greatly affected by the weather / solar insolation of the location. This is particularly problematic for industrial halls with high heat gain from the power-intensive manufacturing processes since most conventional means of heat removal (forced ventilation, cooling tower, etc.) are highly sensitive to the time-varying ambient environment.

In this paper, the focus is to find the optimized building design options on demand side parameters that will maximize the economic benefit of the PV system investment. The energy consumption due to the demand of space conditioning will also be presented, since design options that yield the maximum economic benefit might not consume the least energy, or vice versa.

A case study of a typical industrial hall is presented, which will be investigated with a representative heat gain that is typical for the case of a warehouse. This paper presents some of the results of an on-going project "Sustainable Energy Producing Steel Frame Industrial Halls", which also studies other operation energy related aspects of steel frame industrial halls.

2. Optimizing economic benefit of rooftop PV system through lowering energy demand

This paper is based on the cost-benefit analysis of Lee et al. (2011), in which the monetary return due to electricity generation of PV system (based on savings in energy cost or income from selling of the exported electricity at FIT), is stacked against the annualized cost of the PV system investment. That analysis was demonstrated with a case study of industrial hall, which was conducted for two locations — the German city of Düsseldorf that represents a moderate climate, and the Italian city of Palermo that represents a dry subtropical climate with higher solar insolation for most hours; and was investigated for different process energy scenarios (different heat gains). The result of that particular case study indicates that under the most stringent net FIT scheme (as compared to the other two commonly deployed but more investor-friendly schemes — gross FIT or own consumption FIT), only a warehouse located in Palermo with PV system nearly covered the whole roof yields net benefit. This paper bases upon the assumptions and findings of that case study, and further explores the economic benefit of rooftop PV system through lowering the energy demand by optimizing the building design based on demand side parameters.

2.1 The case study building

The case study adopts the same hypothetical warehouse proposed in the previous study and investigates for the location of Palermo.

2.1.1 The warehouse

The case study building, which represents a typical warehouse, is of rectangular shape measuring 80 m width x 136 m depth x 6 m height. Equipment (computer, forklift etc.) consuming 5 W/m^2 of electricity is assumed. And in order to maintain a lighting level of 500 lx (CEN, 2002), fluorescent lighting consuming 13 W/m^2 is assigned. PV system of 1500 kW$_P$ installed capacity is proposed (maximum size limited by the space of the rooftop).

The workers are assumed to perform light work only. For an industrial hall kind of environment, current guideline (ARAB, 2006) recommends the temperature of the space to be maintained under 30°C during occupied hours to protect workers from heat stress. Heating has to be provided only if the space drops below 18°C during occupied hours. The building is assumed to operate from 08:00 to 18:00.

The building is built with steel cladding on a steel frame with insulation according to ASHRAE standard 90.1 (ASHRAE, 2007a); the walls and the roofs require a minimum resistance value of R-2.3 and R-3.3 respectively. Ventilation rate at 0.3L/s-m^2 is adopted according to ASHARE standard 62.1 (ASHRAE, 2007b).

With the heat released from processes, in practice, cooling is the predominant factor in HVAC energy demand if the industrial halls are not located in extreme cold climate. To effectively cool the space within the set limit, forced ventilation with exhaust fans is deployed to draw in ambient air, which is controlled by two stages ON-OFF strategy triggered at 28°C and 29°C. At stage 1, 60,000 L/s of ambient air is drawn, and at stage 2, an additional 60,000 L/s is drawn. Occasionally, the building during occupied hours does fall out of the desired temperature range with forced ventilation alone. System with ideal control is assumed to satisfy the unfulfilled cooling and heating demand.

For a typical steel frame industrial hall, usually an infiltration rate from 0.1 to 0.5 ACH is expected (ISSO, 2002). For this case study, an infiltration rate of 0.33 ACH is assumed for the optimization, and the range of 0.1 to 0.5 will be applied to the optimized design solution(s) in an uncertainty analysis, in which the infiltration rate will be served as a scenario parameter to be described later.

2.1.2 Demand side design parameters

The building might not be optimally designed in terms of yielding the maximum economic benefit of the rooftop PV system (the objective of this paper), or consuming the lowest energy; if it is designed according to the standard values as prescribed by the building norms. For example, insulation intends to isolate the space from the external elements might not be desirable for building with high internal heat gain, in which the heat is preferably to be dissipated than to retain. Table 1 lists the demand side design parameters that are to be investigated in this study and presents the range of variation for each parameter.

Insulation values range from none to that for climate zone 7 (the coldest zone) as prescribed by ASHARE 90.1 (ASHRAE, 2007a). Mass wall assumes a thickness from none to 40 cm. These values are set to the extremes but are still within practical range; that is, no custom made construction is necessary to implement any of these specifications. Any configuration based on possible combination of these values can be readily built.

2.2 Energy and economic analysis

In order to benefit from the net FIT scheme, the building has to be carefully designed to lower the energy demand such that the PV system can generate more surplus electricity at more hours and export back to the grid at the higher FIT rate. Cost-benefit analysis is therefore an integrated evaluation of both energy and economic aspects.

2.2.1 Energy performance of the warehouse

The building energy performance simulation program TRNSYS is used to perform the energy analysis. TRNSYS is chosen as the simulation environment due to its flexibility and capability in modeling supply and generation side equipment. TRNSYS is called upon by the optimization algorithm and will perform the energy performance analysis for each studied configuration. The result is the hourly energy demand for the occupied hours. TRNSYS is also used to estimate the electricity generation capability at each of the hours for the PV system.

2.2.2 Economic analysis

For each building configuration, the hourly energy demand will be imported to a custom built MATLAB function that will calculate the balance between the energy demand and the electricity generation, at each of the hours. Under the net FIT scheme, the electricity generated by the grid-connected PV system is assumed to be first satisfying the energy consumption of the building; any surplus electricity will be exported back to the grid at the rate of the published FIT, which is at a premium to the electricity price. Table 2 lists the values of the economic parameters used in this study.

At the end of the year, the savings in electricity bills and the earnings based on net FIT scheme shall exceed that of the annualized capital investment cost to justify, economically, the deployment of PV systems.

2.3 Optimization

Optimization is deployed to search for the optimal configuration that maximizes the economic benefit. With three design parameters, there could be hundreds of thousands of configurations if each of the parameters is spread into 50 values within each range. A complete search through all the configurations is computational intensive and technically infeasible. Optimization helps searching for the optimal configuration without the need of covering the whole design space.

2.3.2 Optimization algorithm

ModeFRONTIER is selected as the platform of optimization for its vast selection of optimization algorithms, and its flexible connectivity to energy performance simulation and cost analysis tools, namely, TRNSYS and MATLAB in this case study.

Simplex is a frequently used algorithm for single objective optimization, and is based on linear programing. The success of the algorithm depends very much on the size of the initial search space. If the initial search space is not representative or small, then it will lead to a local search. In this case study, all three design parameters are not linearly correlated with the objective function. Therefore, a large initial search space is necessary but time consuming. For a few trials, simplex converges to and stops at a local optimum.

For this case study, MOGA (multi-objective genetic algorithm) is chosen as the optimization algorithm. Though it is more commonly deployed for multi-objective optimization, its efficiency in searching for global optimum (Poles, 2004) makes it a good candidate.

An initial search space of 50 configurations is generated with Latin Hypercube sampling (LHS). As the optimization progresses through generations, MOGA will move to a more likely search space for each generation. Deviation of the current search space from the previous one depends on the mutation setting, which has to strike a balance between fast convergence and consideration of all possibilities. In this case study, the adaptive evolution option (an option in MOGA) is selected. The result converged roughly after 20 generations.

2.3.3 Robustness of the design solution

The objective of the design is to fetch the maximum benefit for the investment of the PV system. However, the simulation is based on many assumptions that might be subject to change as climate, occupancy pattern, building use are full of uncertainty. As a result, some configurations may be more susceptible to changes than other configurations. An uncertainty analysis based on variation in the assumptions shall be performed to the optimal or near optimal configurations to determine how robust the solutions are.

3. Results and discussion

The energy consumption is comprised of a base energy consumption, which consists of the energy consumed by the equipment and lighting; and the energy consumption for heating, ventilation, and air conditioning (HVAC), which reflects the electricity usage for the fan that provides minimum ventilation for indoor air quality, and the additional energy consumption for forced ventilation that depends on how much ambient air (at a temperature lower than that of indoors) has to be drawn in to remove the released heat of the equipment, and that for auxiliary cooling and heating under ideal control.

In the summer, PV system receives higher solar insolation. However, energy consumption also peaks in the summer, when it is more difficult to maintain the space temperature with ambient air that is at higher temperature. Therefore, an hour-by-hour matching of energy consumption and generation has to be carried out to determine whether (or how much of) the higher output of the PV system can compensate the higher consumption of the building.

Optimization described earlier carries out the energy performance simulation and cost-benefit analysis for each sampled configuration. The mutation setting favors slower convergence such that deviation among generations is less dramatic. The effect can be shown in Figure 1, which presents all 1000 configurations (50 configurations for each of the 20 generations). Due to the slow mutation rate, configurations that have been tested at earlier generations will still be carried over to the later generations.

3.1 Net benefit

The optimization converges at 9.63 €/m^2 in the last three generations without further improvement. The optimization is set to stop after 20 generations. It can be observed from Figure 1 that the unit area net benefit varies from less than 9.1 to more than 9.6 euro per annum.

3.1.1 Impact of demand side design parameters on benefit

There are only three demand side design parameters considered in this case study, namely, resistance of the roof insulation, resistance of the wall installation, and thickness of thermal mass wall. As the optimization algorithm searches through the design space, configurations of different combinations of the three parameters are investigated. Each of the parameters might have different impact to the net benefit. The result is first sorted by the net benefit; for every 50 configurations, the average of the net benefit against the average of each of the three parameters is taken. There are no observed patterns between the resistance of the wall insulation or the thickness of thermal mass wall, and the net benefit. In Figure 2, the average resistance value of the roof insulation is plotted against that of the sorted net benefit for every 50 configurations.

As observed from Figure 2, a decrease in resistance value in roof insulation is in general accompanied with an increase in net benefit. The roof, which is more than 4 times the area of the walls and is subject to even greater solar insolation than the walls, is a more sensitive parameter in the design of industrial halls of large floor space.

3.2 Energy consumption

From the building stakeholders' point of view, the prime consideration might be the net benefit. However, with respect to electricity generation of PV system, configurations with lower energy consumption are in practice more robust solutions, than configurations with higher energy consumption. All energy performance values are predicted through simulation that based on many assumptions, and are subject to uncertainty in those assumptions. Very likely events such as degradation in PV efficiency due to dirt accumulation to more drastic incidents such as complete system break-down, can cause deviation in the predicted energy performance. Therefore, from the generation side of view, solutions with lower energy consumption are more robust since they are more likely to maintain the benefit at the events of less than predicted generation.

3.2.1 Energy consumption of the HVAC system versus that of equipment and lighting

During occupied hours, the building demands a constant power of $5W/m^2$ for equipment and $13W/m^2$ for lighting; that translates into an energy consumption of 562,260 kWh per annum irrespective to the difference in configurations varied on demand side design parameters. By contrast, depending on the configurations, energy consumption for HVAC can range from a low of 59,907 kWh to a high of 89,528 kWh per annum. Out of which, the energy consumption for fan to fulfill minimum ventilation requirement is 5,685 kWh per annum. That implies the energy consumption for heating and cooling (including that for forced ventilation cooling) ranges from a low of 54,222 kWh to 83,843 kWh per annum, a 55% difference. The relationship between energy consumption for HVAC, and the net benefit, is depicted in Figure 3.

From Figure 3, it can be shown that different configurations (and thus different energy consumption) can result in the same amount of net benefit. Or in other words, even the energy consumption can be the same across different configurations, net benefit differs. The observation supports the previous assertion that an hour-by-hour matching of energy consumption and generation is necessary to evaluate the economic benefit of PV installation.

3.2.2 Investigating the sources of energy consumption

The base energy consumption to provide minimum ventilation is 5,685 kWh per annum. The rest of the energy consumption for HVAC is divided across that for cooling through forced ventilation, and for heating and additional cooling under ideal control. Figure 4 presents the energy consumption for different end-uses.

It can be seen from Figure 4 that fan consumes the greatest amount of energy, either to provide minimum ventilation or to fulfill cooling need with forced ventilation. The selected fans operate at a rated power of 6 kW (TWF, 2010) per every 10,000 L/s of ventilation. The selection is in the mid range with more expensive fans rated at power of 1 kW to fans rated at 14 kW, per 10,000 L/s of flow. Most industrial halls of larger floor space are fitted with exhaust fans open directly to the outdoor without duct work, such that pressure difference or space limitation on fan installation are not much of a concern; therefore, it is possible to select more efficient fans at roughly the same cost. The exact selection shall be carefully done in the actual design since the overall energy consumption for HVAC can be greatly reduced with more efficient fans.

During hours when the ambient air is higher than the comfort limit of 30°C, forced ventilation is not effective for cooling and will not be turned on. There are also hours when forced ventilation alone cannot fulfill the cooling requirement. For either scenario, additional cooling is necessary, and is applied to all configurations as shown in Figure 4. The provision of this additional cooling is commonly supplied by rooftop air handling units or radiant panels (for heating as well) in tandem with chillers; in either case, the equipment is running at an efficiency, which consumes only a fraction of the energy that is required under ideal control.

In most investigated configurations, no heating is necessary. For the cases (61 out of 1000 configurations), in which heating is needed, most of them are fitted with below average resistance value for roof insulation, and are corresponding to an above average net benefit. The observation is coherent to what has been observed earlier regarding roof insulation and net benefit. This case study is set in Palermo, Italy, where the building is subject to higher cooling load (due to internal heat gain) than to heating load, it is advantageous to install a less thermally resistive roof for this particular setting.

3.3 Robustness of the design solution(s)

A close-up view of the few most optimized design solutions in terms of net benefit is presented in Figure 5. The solution (S1) that yields the most benefit returns 9.631 €/m^2 per annum. The second best solution (S2) returns 9.626 €/m^2 per annum, and consumes the least energy at 5.51 kWh/m^2. The configuration details of the two solutions are presented in Table 3.

The two solutions perform quite similarly in terms of both monetary return and energy consumption. However, from the building stakeholders' perspective, it is important to know if the solution is robust, that is, if the performance of the solution is susceptible to the dynamic environment that the building is subject to.

A particular concern from the building design point of view is whether the performance is deviated from the prediction if some of the assumed input parameters have changed. One of the greatest uncertainties in the design of industrial halls is the infiltration rate. In general, steel frame construction can be built to high air-tightness. However, doors (industrial size) for loading and unloading are subject to unforeseeable opening pattern. Infiltration rate of 0.1 to 0.5 ACH is what commonly experienced for industrial halls.

Infiltration rate from 0.1 to 0.5 ACH in 20 steps is applied to the two optimal solutions to evaluate the range of uncertainty of the predicted performance — the net benefit and the energy consumption. The results are presented in Table 4.

In fact, for both configurations, the performance under the worst-case infiltration rate deviated quite substantially from the predicted performance at the assumed infiltration rate. The amount of deviation is quite similar for both configurations, and does not suggest if one configuration is more robust than the other. However, it can be observed that solution S1 is more favorable if the building is known not to be operating at lower infiltration rate, while solution S2 is more favorable if the building is known not to be operating at higher rate.

3.4 Optimization as applied to industrial hall design

From this particular case study, a 55% difference in energy consumption for HVAC is observed between the optimized design solutions and the less effective ones. Though energy consumption for HVAC is only a fraction of that for the processes; the absolute amount is still a significant sum that makes it worthwhile to investigate energy saving possibilities. This case study illustrates the potential of applying optimization to effectively search for the best configuration of demand side design parameters. It is also shown that the resistance of the roof insulation is a much more sensitive parameter than the other two parameters. If more design parameters are to be investigated, a sensitivity analysis to determine the most influential parameters is necessary so as to limit the investigation to those parameters that have a larger impact.

4. Conclusions

With reference to the EU-wide directive mentioned at the beginning of this paper, it is of particular interest for Italy to pursue an energy policy that promotes energy generation from renewable energy sources. Grid-connected solar PV system will certainly be one of the options. With findings from this paper, lowering energy demand shall also be taken into consideration. It helps the respective country meeting the target by lowering the energy consumption baseline, and at the same time, provides higher return to the building stakeholders for their investment in PV system.

4.1 Future work

In this study, only the investment cost of PV installation is included in the cost-benefit analysis; the configuration dependent costs, are not included, since they are relatively insignificant as compared to that of PV installation. Inclusion of such configuration dependent costs shall further differentiate the cost effectiveness between two similarly performed configurations. A study that includes more design parameters will also open up new design possibilities. For example, lighting, the largest factor in energy consumption in this case study, might be reduced with daylighting.

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Figure 1. Net benefit as optimization progresses across 20 generations of 50 configurations each.

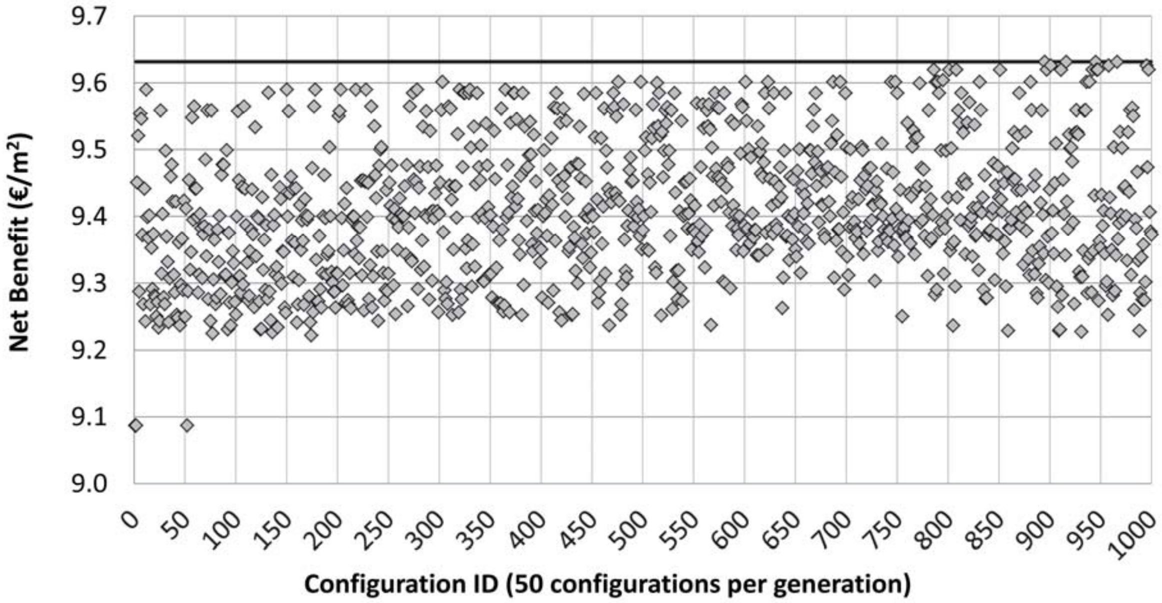

Figure 2. Average net benefit in sorted order per every 50 configurations, and the corresponding average of resistance value of the roof insulation.

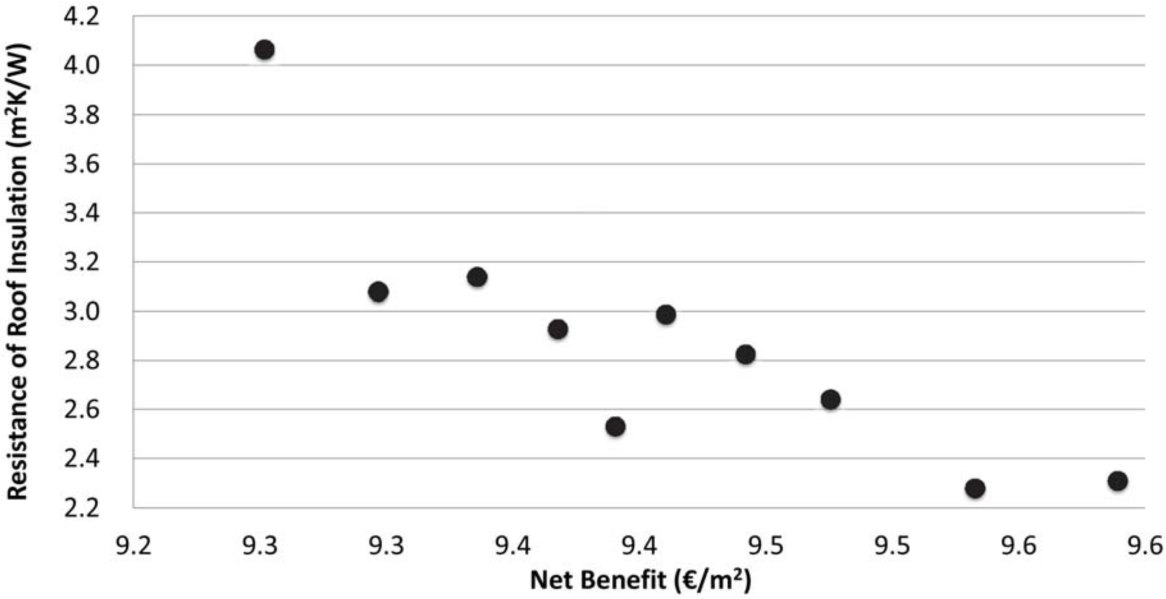

Figure 3. Net benefit and the corresponding energy consumption for HVAC, for all investigated configurations.

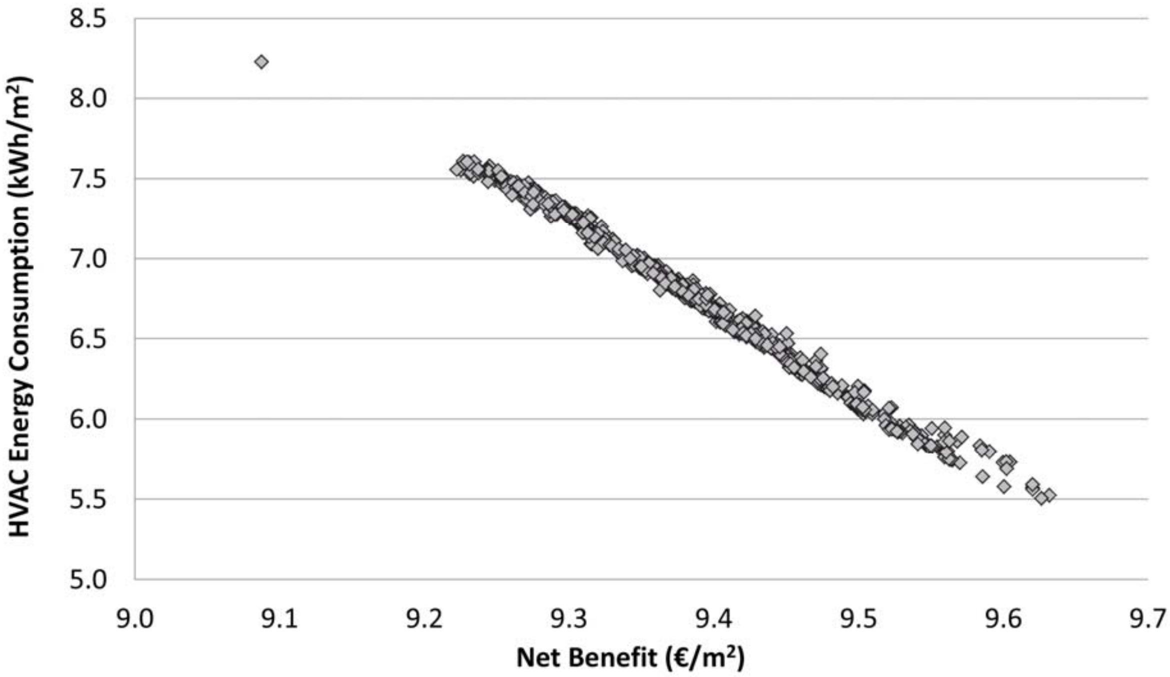

Figure 4. HVAC energy end-uses, configurations sorted by total HVAC energy consumption.

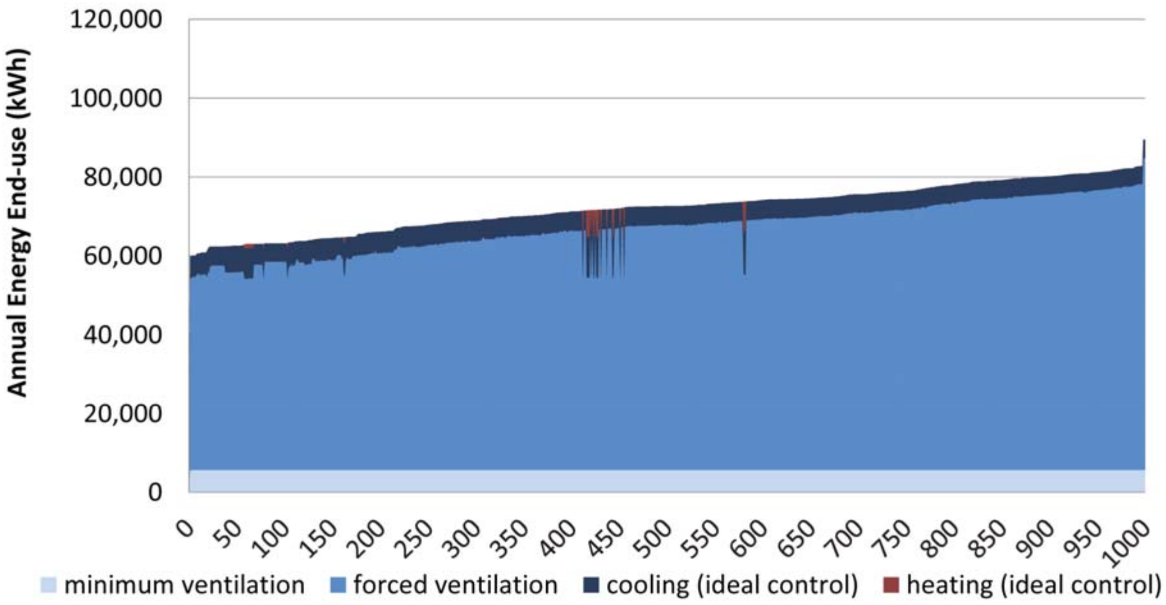

Figure 5. Net benefit and the corresponding energy consumption for HVAC, for the optimized design solutions.

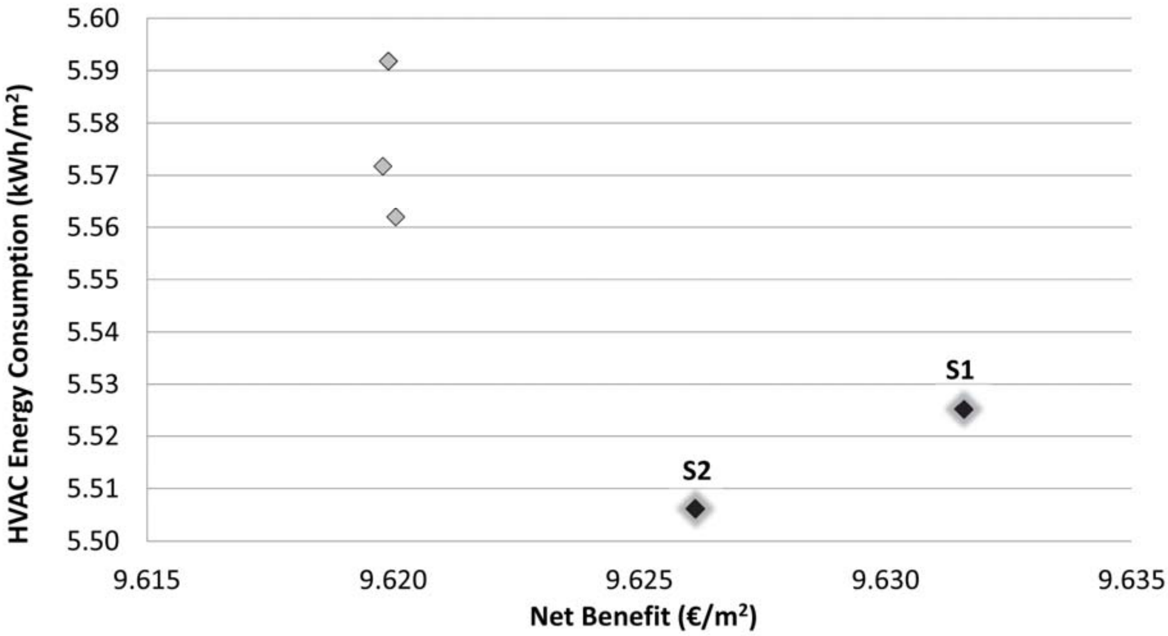

Table 1

Demand side design parameters.

Parameters (unit)	Design range
Resistance of Roof Insulation (m^2K/W)	0.0 – 9.0
Resistance of Wall Insulation (m^2K/W)	0.0 – 9.0
Thickness of Mass Wall (m)*	0.0 – 0.4

* assumes that of concrete wall at a density of 2400 kg/m^3

Table 2

Economic parameters.

Parameters (unit)	Adopted values
Investment cost (€/kWP)	3500 [1]
Life time (yr)	20
Discount rate (%)	2.49 [2]
Electricity rate (€/kWh)	0.1327 [3]
Feed-in tariff (€/kWh)	0.351 [4]

[1] Poullikkas (2009)

[2] EU (2008)

[3] consumption < 2,000 MWh/year (EEP, 2011)

[4] generation capacity 1000 - 5000 kWP (Focus, 2011)

Table 3

Configuration details of two design solutions.

Parameters (unit)	S1	S2
Resistance of Roof Insulation (m^2K/W)	4.50	2.70
Resistance of Wall Insulation (m^2K/W)	4.68	3.24
Thickness of Mass Wall (m)	0.06	0.15

Table 4

Performance of the two design solutions at the default and the worst condition.

Solution S1	Benefit (€/m^2)	Energy (kWh/m^2)
At 0.33 ACH	9.631	5.53
Worst performance at 0.18 ACH	9.065	8.30

Solution S2	Benefit (€/m^2)	Energy (kWh/m^2)
At 0.33 ACH	9.626	5.51
Worst performance at 0.49 ACH	9.019	8.53