Evaluation of a step-by-step million program deep retrofit to passive house with building integrated PV roof and façade

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Background and Introduction

Sweden has an ambitious political goal to be net zero greenhouse gas emissions (GHG) by 2045 which is in line with the EU's goal that the building sector as a whole should reduce GHG emissions by 80% by 2050. A determining factor in reaching these goals in Sweden is the "million program" buildings, a name given to the (mostly) prefab concrete buildings built in the 60s and 70s to reach a goal of one million additional homes[1]. Needless to say, these buildings are in great need of renovation today, and that poses both a problem and an opportunity[2]. Namely, there is a lack of cost effective renovation solutions that both reduce energy demand and generate renewable energy.

Building Integrated Photovoltaics (BIPV) applied on roofs and façades of existing buildings during renovations is one such potentially cost-effective solution. If one looks at only the roof area for all buildings in Sweden (approx. 1100 km^2)[3], the contribution to total electricity production would be on the order of 80 TWh per year, which is more than half of Sweden's total electricity use. If this type of solar capacity was installed on the Swedish building stock gradually as roofs and façades were renovated the extra cost to society would be vanishingly small since the price of some solar modules (200-300 kr/m^2) are now cost competitive with traditional façade and roof materials[4].

When BIPV is part of a thermal envelope renovation the energy use in the building can also be reduced by 50-80%, and up to 100% of the remaining energy demand can come from the BIPV. So, a BIPV product that can replace traditional building materials such as fiber reinforced concrete, sheet metal, bricks and fiber polymer boards opens up a large potential to improve energy performance of buildings (mostly through insulation and airtightness) and at the same time reduce the environmental impact of the electricity generation system as a whole (with PV). The challenge is to create a BIPV system that is inexpensive to install, fulfills the façade and roofs' functions without compromising the solar modules production, and has a low life cycle embodied energy.

[1] Nationalencyklopedin, miljonprogrammet. http://www.ne.se/uppslagsverk/encyklopedi/lång/miljonprogrammet (accessed 2018-01-07)
[2] Warfvinge, Catarina. "Mycket energi att spara i miljonprogrammet!." *VVS-forum-värme och energi*. No. April. 2008.
[3] Kamp, Sigrid. "Sveriges potential för elproduktion från takmonterade solceller: Teoretisk, teknisk och ekonomisk analys." Lund University. 2013.
[4] Sukurica, Amer. "Livscykelkostnad för tak och fasad." Högskolan i Halmstad. 2013.

Kollektivhuset Stacken, a classic Swedish “million program” building with 35 apartments in Göteborg, which has long been run as a cooperative, has demonstrated a cost effective step by step deep retrofit to Passive House standard with a building integrated PV façade and roof. The renovations technical details of which can be found in the previous article in this series[5]. In short, the existing concrete façade was externally insulated and covered with thin film solar modules and more effective crystalline solar modules were installed on the roof. New passive house certified doors and windows, and demand controlled ventilation coupled to a heat recovery unit have been installed in the building although installation of vacancy sensor based lighting is still underway and final ventilation adjustments have not yet been completed. Finally, sensors to monitor the façade elements, cold and hot water use, ventilation flows, electricity, temperature and humidity in each apartment were installed.

The pilot project was led by members of Kollektivhuset Stacken in collaboration with partners Effektiv Bygg, Chalmers Tekniska Högskola, Passivhusbyrån, Helhetshus architect studio, Rockwool, i2 Smartwin, Passivhuscentrum, and Ekobanken. Financiers for the construction include Naturskyddsföreningen, Energimyndigheten, and Västra Götalandsregionen. Technical support has been provided through inclusion in EuroPHit, a Passive House project of the European Union. Figure 1 shows the completed building in its surroundings next to identical unrenovated buildings on the same street.

[5] Norwood, Z., Theoboldt, I., Archer, D-E. Step-by-step deep retrofit and building integrated façade/roof on a ‘million program’ house. Passive House 2016 Conference Proceedings. 2016.

Figure 1. Kollektivhuset Stacken with BIPV façade and roof next to neighboring unrenovated million program “star” buildings. Photo courtesy of Badenfelt and RISE.

This article aims to summarize the findings and temperature normalized performance of the building in 2017 compared to normalized performance before the project began (2015) and projected performance as calculated at the projects onset. A financial review of the pilot project will also be presented.

Methodology

The analysis presented here is a comparison between the modelled and actual results from the project. The calendar year 2017 is used for the actual performance results, but the construction of the building envelope was not officially complete until November, 2017, so this period includes data when the building was under construction. Vacancy controlled lighting and final adjustments of the ventilation system are still incomplete as of the writing of this article. The changes to the thermal envelope however were very nearly completed by the onset of 2017, so it is reasonable to include the whole year of data for heating and electricity demand for comparison purposes. Solar energy production did not begin until October, 2017 however, so it is too early to make any longer comparisons of modelled to actual production.

The building energy model is done in the Passive House Planning Package (PHPP)[6] and the solar energy production model uses the System Advisor Model (SAM)[7] with the built in weather data for Göteborg Landvetter airport, about 20 km from the project site which lies in the Bergsjön neighborhood of Göteborg.

Results and Discussion

Table 1 summarizes the actual performance of this 9-story apartment building pre- and during/post-renovation compared with the modelled performance. Modelling is done both according to certification requirements for the International Passive House standard (at 20°C indoor temperature) and with the increased indoor temperature (to 22°C) and more realistic internal loads to more accurately reflect actual use. Monthly hot water consumption for the historic 2015 and 2017 data is estimated to be the average district heating demand during 3 summer months (June, July, and August) when active space heating is disabled in the building. Space heating is thereby calculated by subtracting the average summer hot water demand from the typical year corrected district heating demand for each month.

As seen in the table the total space heating demand during 2017 has been decreased by more than two-thirds from 2015, and electricity by more than a fifth. Actual hot water usage is used in certification to avoid overestimation, however total space heating demand in 2017 is higher than projected by PHPP even given the extra 3.6 kWh/m^2*a due to the increased

[6] Feist, Wolfgang, et al. "Passive house planning package v. 9.3" *Passivhaus Institut, Darmstadt,* 2015.
[7] Dobos, Aron, and P. Gilman. *System advisor model*. Tech. Rep.(National Renewable Energy Laboratory, 2012) NREL Report No. TP-6A20-53437, 2012.

indoor temperature. There are several possible explanations for the higher space heating demand.

One explanation is windows being tilted open for many hours during the heating season which has been observed in the building especially under the fall months (photo evidence exists on the www.stacken.org website).

To calculate the influence open windows during the heating period give, the ‘air change rate through window ventilation’ tool on the 'SummVent' page of PHPP has been used. The temperature difference between indoor and outdoor temperature during the heating period is clearly much higher than during the summer, and the wind speeds are higher as well. Leaving those two factors set on the summer settings with wind speed for more exposed buildings and locations should therefore provide a conservative estimate for these losses. For the calculations, 8 pairs of windows, to allow for cross ventilation, were used (one on each dwelling floor), although the "chimney effect" due to the difference in height was ignored since it is assumed that the flats are separated enough so that this effect would not occur. The resulting air exchange rate relates to the entire indoor volume and is without heat recovery and can therefore be modeled as higher infiltration rate (i.e. the building is "less tight") or as additional ventilation with no heat recovery. The opening time was set to 8 hours per day. A resulting additional 19.2 kWh/(m^2*a) heating demand results in the PHPP, dividing by eight to represent one pair of windows would therefore result in 2.4 kWh/(m^2*a) increased heating demand. In summary, an approximately 20% increase in total space heating demand for the *entire building* results from one pair of open windows. A single window tilted opened for 8 hours a day would lead to about a fifth of that loss (0.4 kWh/m^2) according to the model. Hence, the potential for open windows significantly increasing heating demand is a concern in highly energy efficient buildings.

Secondly, it is important to note that the typical-year normalized district heating data provided by the local utility (Göteborg Energi), based on a heating degree day method, can be less accurate for a passive house than for a typical building because a passive house does have a significantly lower balance point temperature. In 2015, pre-renovation (when the building had a more typical balance point temperature) the heating degree day normalization method is appropriate. We have therefore included the actual 2017 and normalized 2015 heating demand in Table 1. Using actual weather data in 2017 results in less than 0.4 kWh/m^2*a difference in space heating compared to typical data in PHPP.

Thirdly, differences in the amount of cloud cover and resulting solar gains can be significant from year to year, resulting in an approximately 2 kWh/m^2*a increased heating demand for 2017 compared to modelled. Together, these three factors can more than explain the approximately 4 kWh/(m^2*a) increased heat demand as compared to modelled.

	2015, kWh/m^2*a	**2017, kWh/m^2*a**	**Modelled (certified), kWh/m^2*a**	**Modelled (22°C), kWh/m^2*a**	**2017 compared to 2015**	**2017 compared to certified**	**2017 compared to modelled (22°C)**
Total	75	31	24	29	- 59%	+ 29%	+ 7%

district heating demand							
Hot water demand	11	11	12	12	+/- 0%	n/a	n/a
Space heating demand	64	20	12	17	- 69%	+ 66%	+ 18%
Electricity demand	40	31	31	31	- 23%	+/- 0%	+/- 0%
Solar PV Production	0	n/a	25	(25)	n/a	n/a	n/a

Table 1: Annual actual pre- and during/post-renovation compared to modelled energy demand and production.

A more detailed month by month breakdown of slightly more than five years of heating and electricity demand can be seen in Figures 2 and 3.

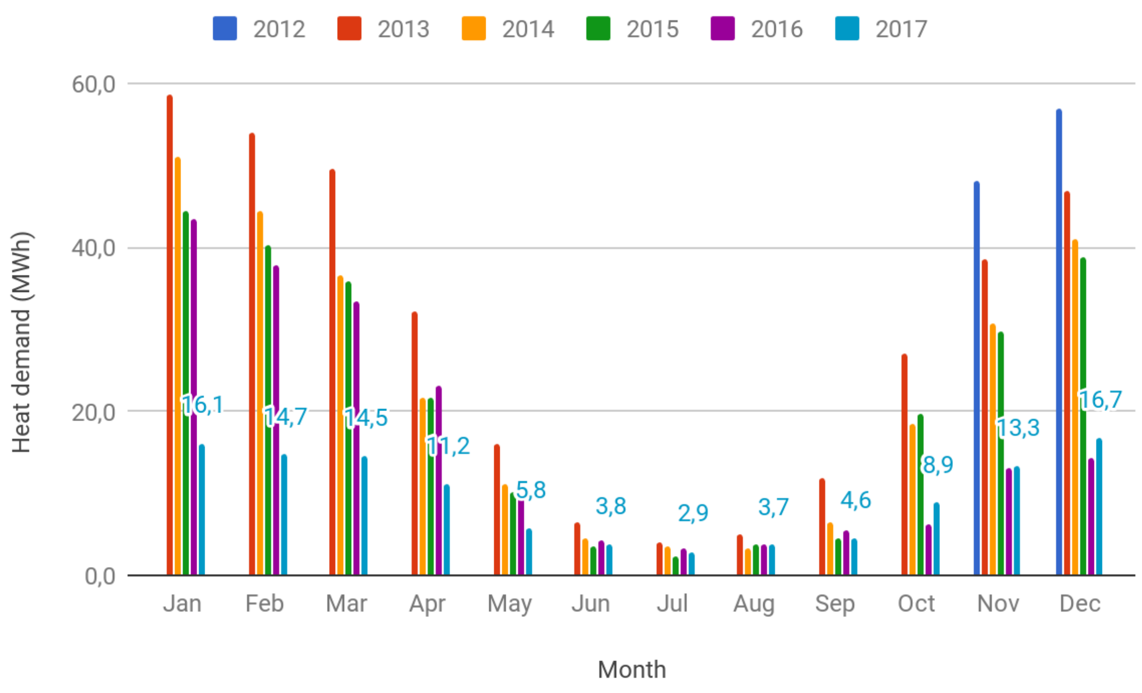

Figure 2. The building’s typical-year normalized heating demand from November, 2012 through December, 2017.

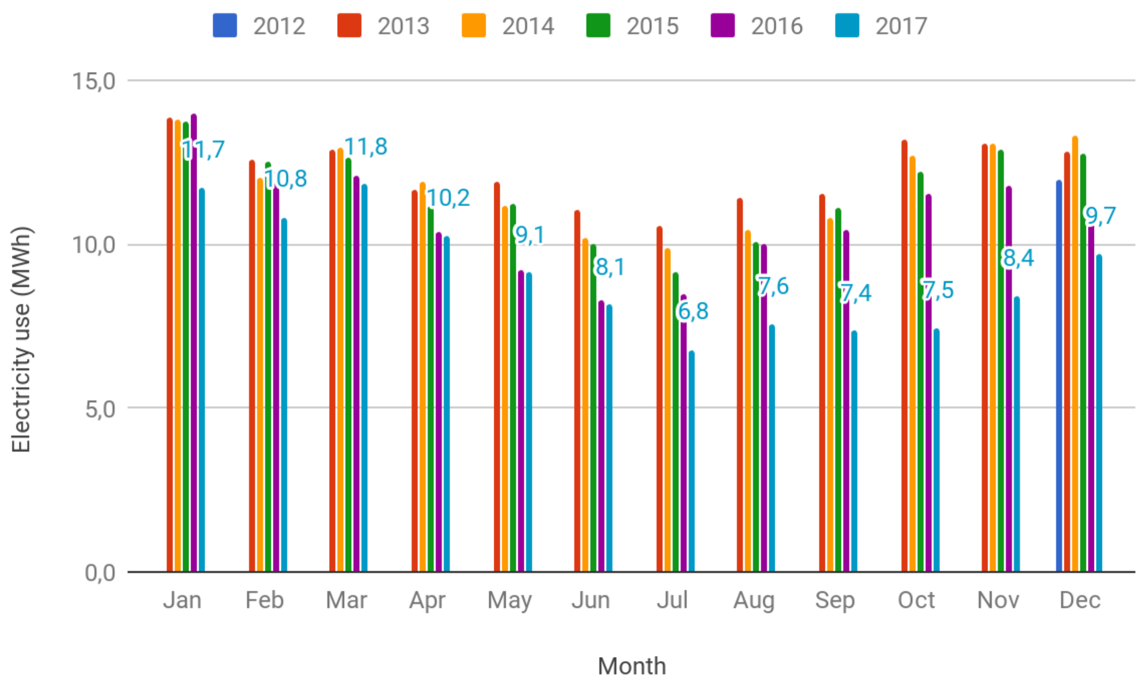

Figure 3. The building's electricity use from December, 2012 through December, 2017. Note that, due to metering problems, some solar PV production is included in the October through December, 2017 results and reduces the appeared demand somewhat.

Figures 4 and 5 show a time series of historical electricity consumption (2015 and 2017) and projected and actual solar PV electricity production during one winter week. The night time electricity demand has been reduced almost 50% from 2015 to 2017 due to a combination of demand controlled ventilation, more efficient kitchen appliances, and more efficient lighting. Actual solar PV production for the 3 full months it has been in operation is also less than predicted although the reason for this has not yet been determined. Some possible explanations being explored are unusually cloudy November and December months (compared to typical months as modelled), shading effects, metering problems, and possible wiring problems with some solar strings.

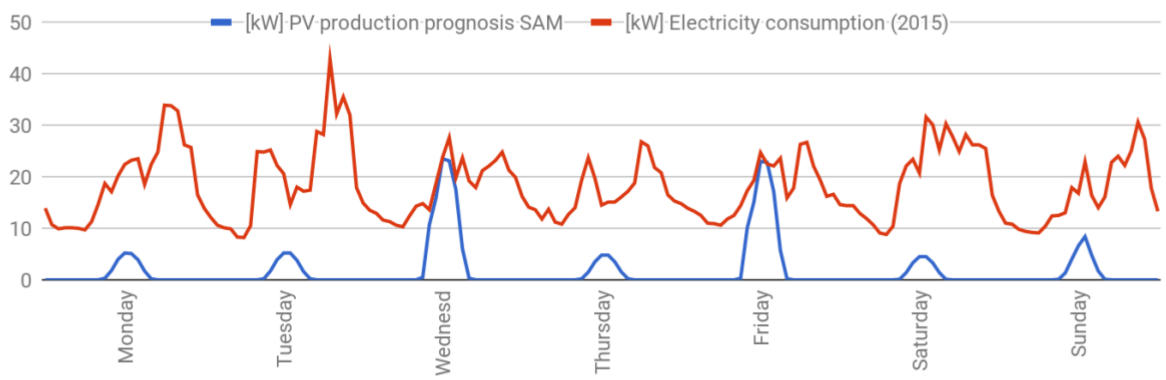

Figure 4. SAM modelled PV production prognosis and one week of historical electricity consumption in December, 2015.

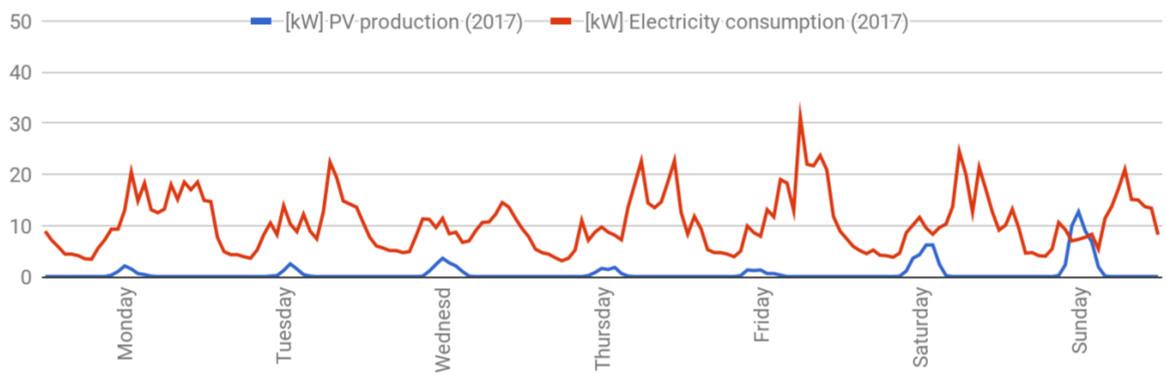

Figure 5. Actual production and consumption data logged by the PV inverters during one week in December, 2017.

Economy

The cost of adding building integrated PV at the same time as applying external façade insulation has been demonstrated on Stacken, while at the same time a spin-off project at Chalmers University of Technology has demonstrated similar BIPV concepts on the façade and roof of an existing campus student housing building, HSB Living Lab, albeit without the added insulation. Using the experiences from these two projects some conclusions and comments about costs can be made:

- The total cost for the renovation of Stacken was approximately 350 EUR/m^2 floor area (A_{temp})
- Experiences from the HSB Living Lab BIPV façade show that the average time for installing frameless amorphous silicon (a-Si) PV modules was 73 minutes per m^2. At a labor cost of 50 EUR/hour this is 61 EUR/m^2 façade area.
- The material cost for a-Si modules for the Stacken project was 18 EUR/m^2 sourced from a large canceled solar power plant project. Standard costs for a-Si modules is closer to 25 EUR/m^2, although the low efficiency (~6.5%) modules used in these projects are not commonly manufactured anymore.
- Installation time for Rockwool's REDAir FLEX mineral wool insulation system is, according to the manufacturer, 8.5 minutes per m^2, including shaping of isolation batts, drilling holes for fastening screws and attaching the batts. At a labor cost of 50 EUR/hour this is 7 EUR/m^2 façade area. Time estimation from Rockwool does however seem to be significantly lower than reality and it does not include logistics. A more realistic installation cost would be perhaps two or three times higher.
- Material cost for the Redair flex system delivered to Stacken was 30 EUR/m^2 complete with all components, and without discount this price might be closer to 40 EUR/m^2.

The discounted payback time of the project is calculated to be about 16 years, as shown in the cash flow analysis (Figure 6). Out of the total budget of 1.3 M€, 64% is from a bank loan (2% interest rate) and 36% from public grants. The prognosis for revenues from the investment related to the Passive House retrofit are:

- General maintenance of the building that would have had to made if the Passive House retrofit had not been made amount to about 40 k€/year for the coming 14 years, including amongst other things cleaning, repainting and sealing the former façade as well as whole building window replacement.

- Reduced district heating 15 k€/year.
- Electricity from BIPV sold to grid 3 k€/year.
- Electricity from BIPV consumed within the building reducing the amount of bought electricity, 6 k€/year
- Reduced electricity consumption thanks to, among other, less air flow in the ventilation heat exchanger and more efficient lighting, 4.4 k€/year.

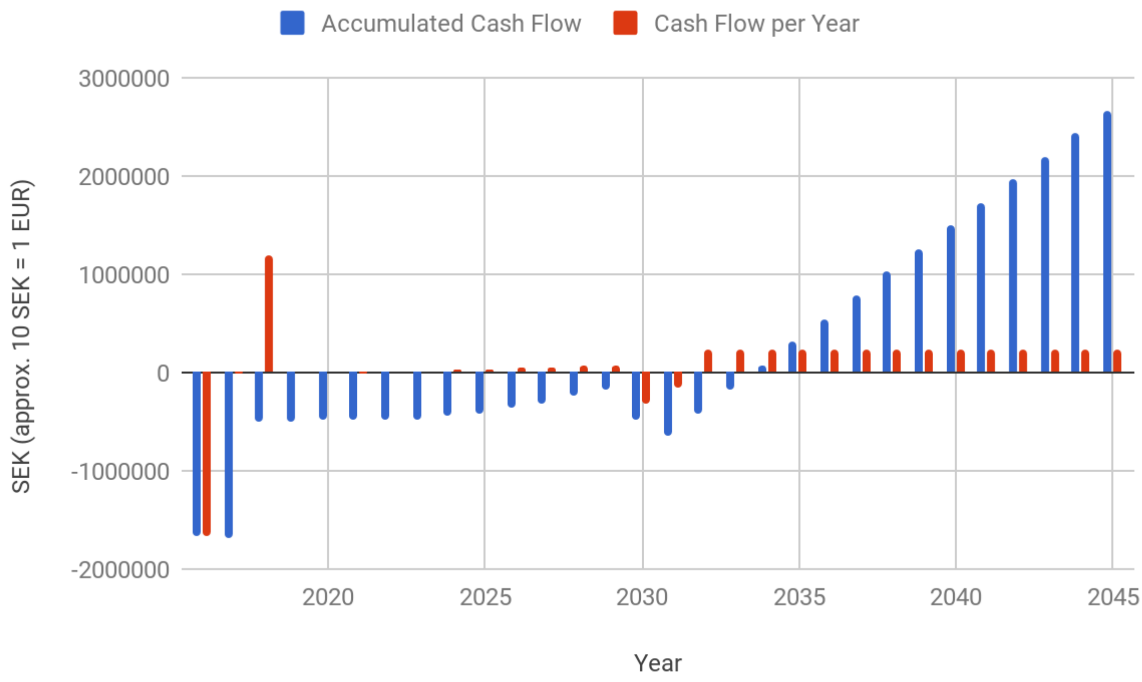

Figure 6. Cash flow analysis of the Stacken passive house project.

Conclusions

The Stacken project has demonstrated that bringing a nearly 50-year old concrete apartment building to the the new-built International Passive House standard can be economical when done in combination with building integrated photovoltaics. Costs for the façade can be as low as 100 - 150 EUR/m^2 façade area with external insulation based on project experience at Stacken. Without insulation costs, BIPV façades can be as low as 80 EUR/m^2 as demonstrated at another project, the HSB Living Lab. These prices are without the costs of scaffolding and building site preparation, which in Stacken's case inclusive profit and risk accounted for nearly 40% of the total cost. In the authors' experience these additional costs can vary substantially, and can be a very large portion of some construction bids.

Furthermore, by avoiding the aluminum racking and aluminum frames associated with traditional solar PV a significant reduction in the total embodied energy of these solar BIPV arrays can be achieved, at the same time that the new façade and roof materials are avoided. These factors make such an approach both environmentally friendly and economically beneficial for projects where roofing and façade materials are being replaced anyway.

Stacken appears to be on track to perform as certified, as the first year of service (including most of the year under construction) has shown a 69% decrease in space heating demand and a 22% decrease in electrical demand. However, a couple of areas to monitor are inhabitants opening windows during the winter and the potential large affects this can have on total heating demand, indoor temperature, and the solar PV production which still needs to be fully verified during the sunnier seasons. In summary, Stacken has been a unique project where none of the local construction companies had any experience with solar BIPV nor passive houses, and therefore similar future projects should be expected to come down the learning curve relatively quickly.