The influence of Swedish households' everyday activities and electricity-use patterns on the utilization of small-scale photovoltaic systems

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Abstract
Although many European countries have developed extensive subsidy programmes for photovoltaics (PV) and other small-scale technologies for electricity generation, the interest in such programmes from Swedish legislators has been low. Subsidies for grid-connected PV systems for public buildings have been offered, but so far no initiatives have been directed to residential buildings. A recent inquiry suggests net metering for small-scale electricity producers, which would improve the economics somewhat, but the PV electricity would still be several times more expensive than the utility electricity. Nonetheless, private initiatives have begun to emerge in which companies offer small, yet expensive, systems for photovoltaics and wind power to residential customers.

The purpose of this paper is to investigate differences in the load-matching capability of PV systems in a number of Swedish households. Seven measurement series of end-use-specific household electricity on 10-minute intervals are used, together with modelled PV generation with the same resolution. The households have participated in interviews that give insight into the routines and habits behind their electricity use. Differences in the daily distribution of loads are determined for various system sizes. The habits behind the electricity loads and the resulting differences in load matching are discussed based on the interviews. Considerable differences between the households are found both in terms of total daily load profiles and of end-use composition, and explanations for these findings are suggested by the interviews.

Introduction
Installations of grid-connected photovoltaics (PV) for residential end-users of electricity have been increasing in Europe over the last decade. Most notably, this has been the case in Germany, where the installed grid-connected power reached 3.8 GW_p in 2007, a consequence of generous subsidy schemes based on feed-in tariffs. In the Scandinavian countries, the installed PV power is much lower. In Sweden, the total grid-connected power in 2007 was a mere 1.7 MW_p and in Norway only 0.1 MW_p (IEA-PVPS, 2008).

Public support for PV has been, and is still, low in northern Europe. The initiatives in Sweden have thus far been limited to support for installations in public buildings. However, more focus has been directed lately to residential customers through an inquiry into facilitation of grid connection of small generation units (SOU, 2008). One important suggestion is net-metering for small-scale electricity producers with a billing period of one month, meaning that all production that does not exceed the consumption under one month is valued at the same price as bought electricity.

Although these legislative proposals have not yet been decided, private companies offering residential customers small PV and wind-turbine systems have begun to emerge. The most well-known in Sweden at present is probably the *EgenEl* initiative (EgenEl, 2009). The PV systems offered for sale or hire by the company are small and designed to be applied to a balcony or a roof (300 W_p and 540 W_p, respectively). With no subsidies – even with net metering – these systems are far from cost-effective. However, as shown in Palm & Tengvard (2008) ideological motives are important for those buying and showing interest in the EgenEl products.

With a grid-connected PV system, all surplus power produced by the system (i.e. the production not covered by the load) can be delivered to the grid. Imagining a scenario with extensive integration of distributed PV into residential areas, this puts constraints on the grid at times when the production is high and the load is low. To study this effect, more detailed knowledge of households' load profiles is necessary. The load matching capability for aggregate domestic load has been studied for Sweden in Widén et al. (2009) but it is also interesting to study the variation between individual household loads and the reasons behind these.

An important result of the recent measurement survey of the Swedish Energy Agency (SEA) is the large variation in electricity demand between different households, even within the same basic categories (Bennich, 2008). This variability was also noted for the 14 households studied in an in-depth study of everyday activities related to electricity use (Karlsson & Widén, 2008). In the latter project, annual electricity demand figures were studied. When analyzing the utilization of photovoltaic systems, however, the daily load pattern is more important as it determines the match to the PV profile and the resulting net power demand and production.

AIM AND LIMITATIONS OF THE STUDY

The aim of this study is to show how much the utilization of a small-scale photovoltaic unit differs between households, but also to reach beyond the figures to grasp what determines the electricity-use patterns and how they relate to the everyday lives of the household members. The approach of this study is therefore both quantitative and qualitative. Differences in load matching are determined and analyzed for a small set of households and how these differences depend on the domestic electricity demand patterns is shown. The differences are also discussed based on detailed interviews with the households about their energy-related habits.

Measurements and interviews from seven households in the SEA's behavioural study are used. The electricity demand of these households was measured in the summer, which is the critical period from the photovoltaic load-matching perspective. Realistic PV system output is modelled, based on synthetically generated insolation data, and is used to determine the load matching.

The study is limited in a number of ways. Obviously, the number of households is small and general conclusions about load matching in the built environment should not be drawn from these analyses (this has been studied separately on large scale in Widén et al. (2009)). Rather, the intent is to show examples of the variability and its causes for a limited number of households, but for which the degree of detail is high, a perspective which is lost in most large-scale studies. One important practical limitation of the study is that measurements, interviews and time diaries were not planned with the intention of studying load matching. Although households were not asked specific questions about load matching, the data essential for the study could be extracted.

Material

ELECTRICITY DEMAND DATA

The detailed series of measurements of household electricity demand used in this study were previously used in the behavioural study Karlsson & Widén (2008). The latter study is part of a larger project run by the SEA, designed to improve the statistics for the built environment in Sweden. The measurements, which started in the autumn of 2005 and ended in the summer of 2008, covered around 400 households mainly situated in the Mälardalen region in mid-Sweden. A minor set of reference households were also located in northern and southern Sweden. Most measurement data were collected during one month and around 40 households were measured annually.

The measurements were made on individual appliance level and cover a majority of the most frequently used electrical appliances. Every single appliance could not be monitored but the goal was to minimise the residual, that is the difference between total demand and the sum of all specific measurements. Both detached houses and apartments were included. The measurements were performed in 10-minute intervals, making it possible to study in detail the daily variations in demand.

End-use-specific measurements for seven annually measured households from the behavioural project are used in this study. The measurements were all made in the summer of 2006. Seven monthly measured households were also analysed in the SEA's behavioural study but since these were measured in mid- or late autumn they were not deemed suitable for the load-matching analysis, for which the summer is the critical period. The start- and end points of the measurement series differ, but they all contain the period May through July, which was chosen for analysis. During this period a major proportion of the annual insolation takes place and the irradiation intensity is at its highest.

Only specifically measured household appliances are included in these data, meaning any additional miscellaneous demand is not taken into account. However, the additional demand, i.e. the residual, makes up only a minor fraction of the total load in the households. Mean load curves of the seven households, with assumed names, for the three-month period are shown with 10-minute resolution in Figure 1.

PHOTOVOLTAIC SYSTEM OUTPUT DATA

Synthetic high-resolved insolation and weather data can be generated for an arbitrary location using the climate database and simulation tool Meteonorm 6.0 (Meteotest, 2009). 10-minute series of solar irradiance were generated, based on weather station data for Stockholm, Sweden (59° N, 18° E). PV system output was simulated from these data with a model described in Widén et al. (2009), based on Duffie & Beckman (1991). The model uses direct and diffuse irradiation and ambient temperature as input and returns the PV power output at maximum-power-point operation (maximum efficiency), with losses in additional equipment such as inverter and cables taken into account. The mean daily production profile for the three-month period is shown in Figure 2. The time frame 9-17 (with summer hour shift) is shown, during which time the main daily production takes place.

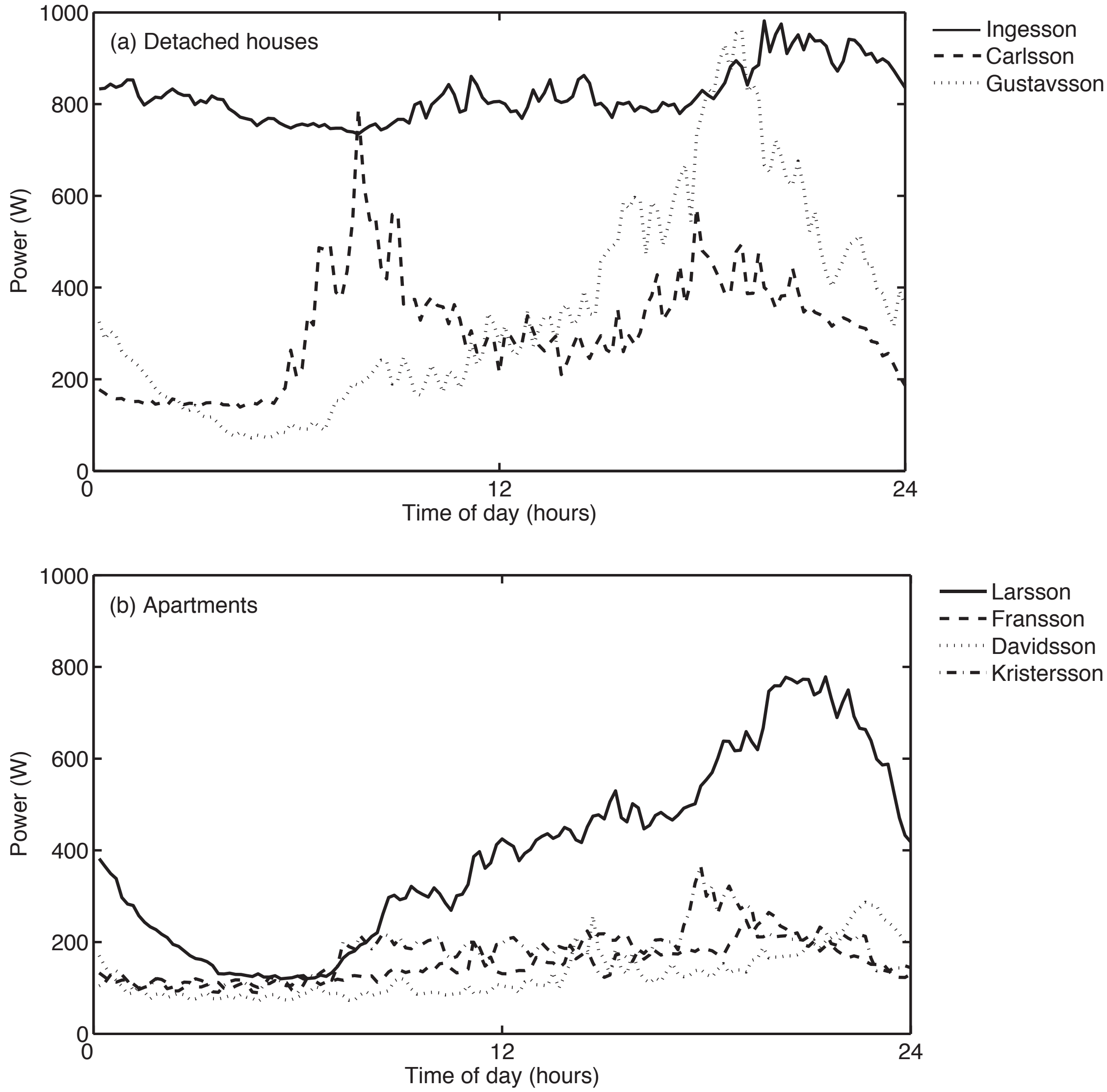

Figure 1. Mean daily load curves for the period May – July.

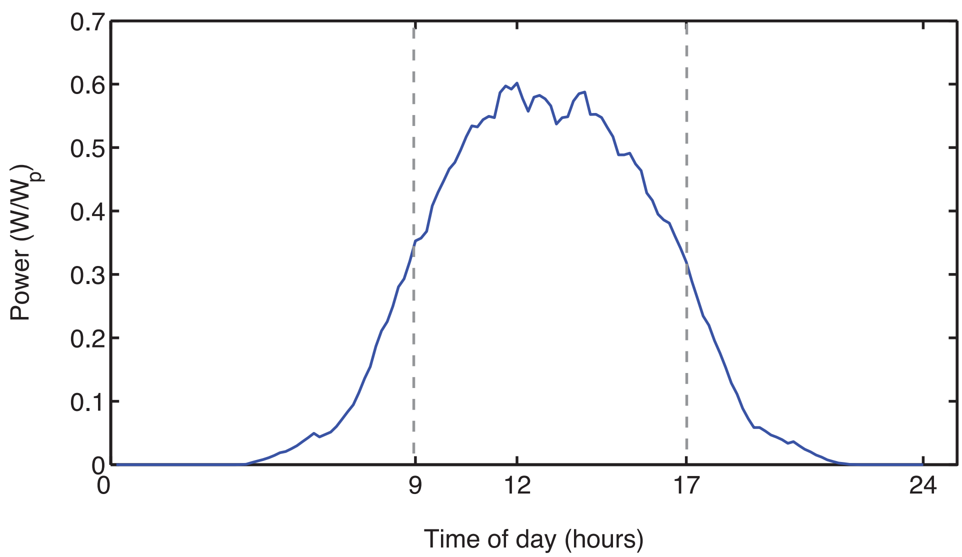

Figure 2. Mean PV system output for the period May – July. The time frame with 80% of the daily production is indicated.

Table 1. Description of the seven households.

Household	Sex and age of the members	Type of dwelling	The womens' occupations	The mens' occupations
Carlsson	man 66, woman 60	detached house	part-time outside the home	full-time outside the home
Davidsson	man 62, woman 62	apartment	part-time outside the home, is part-time on the sick-list	full-time outside the home
Fransson	man 48, son 12	apartment		full-time both in and outside the home
Gustavsson	man 68, woman 59 son 20	detached house	full-time outside the home	pensioner, son: full-time outside the home
Ingesson	man 50, woman 50 son 24	detached house	full-time outside the home	full-time in the home, son: full-time outside the home
Kristersson	man 39, woman 33 daughter 0,5	apartment	on parental leave	full-time outside the home
Larsson	man 52, woman 43 sons 17 and 15	apartment	full-time outside the home	full-time outside the home

INTERVIEWS

All 14 households participating in the SEA's behavioural study (Karlsson & Widén, 2008) were interviewed once in their dwellings. On these occasions each household was represented by one to three persons. The interviews were structured around open-ended questions dealing with the informants' attitudes towards energy issues in general and their perceptions of their own daily habits and related electricity use within three categories of use: "food and cold storage", "entertainment and information", and "washing and cleaning". The latter asked for household members' descriptions of who uses which appliances, when and where the use is taking place, for what purposes, and, in households with more than one member, how this electricity use is distributed among the members. The interviews were taped and transcribed verbatim. The seven households referred to in this paper are briefly described in Table 1.

Households Davidsson, Fransson, Kristersson, and Larsson were among the five households that also wrote time-diaries during two weekdays and two weekend days and kept logbooks about their use of stoves, microwave ovens, TVs, computers, washing machines, and drying appliances that were installed in the dwelling. After the compilation of this material and the measurement data these five households were revisited and follow-up interviews were made and taped, but not transcribed.

Load matching analysis

PV system output and household load profiles were studied for total household loads to determine the overall matching, and for all end uses to determine if some end uses by default are more well-matched to the load than others. The direct matching for total load is calculated at each 10-minute interval, while in the end-use analysis the daytime distribution of loads is studied.

DIRECT MATCHING BETWEEN TOTAL DEMAND AND PRODUCTION

In the following analysis, two base cases were studied, based on the system sizes in the EgenEl initiative (EgenEl, 2009). For the apartments a 'balcony electricity' system was assumed (300 W_p, tilt 90° due south) and for the detached houses a 'roof-top electricity' system (540 W_p, tilted 45° due south). These base case systems are rather small, in that they produce annually only a fraction of the annual energy demand. The system peak powers were also increased in steps to correspond to larger system sizes.

The fraction of production covered by the load was calculated for different system sizes and is shown in Table 2 for apartments and in Table 3 for detached houses. The figures thus show how much of the total production during the studied period is used directly by the households and how much is delivered to the electricity grid. For example, as shown in household Larsson in Table 2, 94% of the production is utilized directly and 6% is delivered to the grid with a 300 W_p system. When the system size is increased to 1500 W_p, the overproduction also increases, so that 66% is utilized directly and 34% is delivered to the grid.

In the same tables, the maximum system size for which at least 90 % of the production is used directly is shown. It is evident that there are quite large variations between the households in terms of total loads and to what degree the systems are used directly. There is a difference between apartments and detached houses, but this difference is not unambiguous. In general, a major part of the production is utilized directly for the basic system sizes. Larger systems – which in general are more interesting since the amount of produced electricity is more similar to the size of the total load for these months – are utilized directly to a lesser degree. A system with a total period output comparable to the load matches about one third of the load. For a system with a production comparable to the *annual* load, the matching is considerably worse (although not shown here).

Table 2. Load-matching variations between apartments.

Fraction of production covered by load at different system sizes (%)					
Household	*300 W_p*	*500 W_p*	*1000 W_p*	*1500 W_p*	*Total load*
Larsson	94	88	76	66	1046 kWh
Fransson	93	79	57	45	441 kWh
Davidsson	80	63	43	33	326 kWh
Kristersson	85	75	55	43	454 kWh
Total production	84 kWh	140 kWh	280 kWh	420 kWh	

System size limit to cover 90 % of production with load		
Household	*Peak power (W)*	*Total production (kWh)*
Larsson	450	126
Fransson	340	95
Davidsson	200	56
Kristersson	200	56

Table 3. Load-matching variations between detached houses.

Fraction of production covered by load at different system sizes (%)				
Household	*540 W_p*	*1000 W_p*	*1500 W_p*	*Total load*
Ingesson	100	99	89	2105 kWh
Carlsson	97	87	77	2396 kWh
Gustavsson	85	66	54	1183 kWh
Total production	246 kWh	455 kWh	682 kWh	

System size limit to cover 90 % of production with load		
Household	*Peak power (W)*	*Total production (kWh)*
Ingesson	1450	660
Carlsson	850	387
Gustavsson	430	196

MATCHING OF PARTIAL LOADS TO THE PV PROFILE

The variation in load matching obviously depends on the total load during the hours of insolation. It is therefore interesting to study more closely both the overall power level and the daily variation in load. To explain differences in matching, the critical time frame is 9-17 (with summer hour shift) when 80% of the insolation on an average day takes place (for a system located in mid-Sweden directed to the south and tilted 45 degrees). The interesting question is how high the electricity demand is during these hours and which end-use categories account for this demand.

Figure 3 shows partial loads during the time frame for an average day of the three-month period. Differences between the households are evident. Once again, there is a difference between apartments and detached houses, although one apartment (Larsson) has a higher daytime demand than two of the detached houses. The composition of demand is highly variable, although certain categories, such as cold appliances and cooking, recur more evenly between the households. The main differences are in the computer categories, washing and drying and dishwashing. Use in the two latter categories depends on whether the required appliances are installed. In this regard there is a difference between apartments and detached houses.

Table 4 shows, for each end-use category, what fraction of the total load is demanded during the 9-17 time frame (for an end use evenly distributed over the day the fraction is 33% by default). Certain end uses obviously occur more frequently during day time, but the variation is large between the households. Washing and drying, dishwashing and cooking have high percentages in a few cases, although not in general. It is interesting to describe why these differences in demand level and demand fluctuations occur. To do so, a qualitative investigation of the habits behind the electricity use is required, which is described in the following section.

Differences in electricity-use patterns

From the graphs and tables in the previous section, a few characteristics of the different loads can be identified. The Fransson, Kristersson and Davidsson households all have, in comparison,

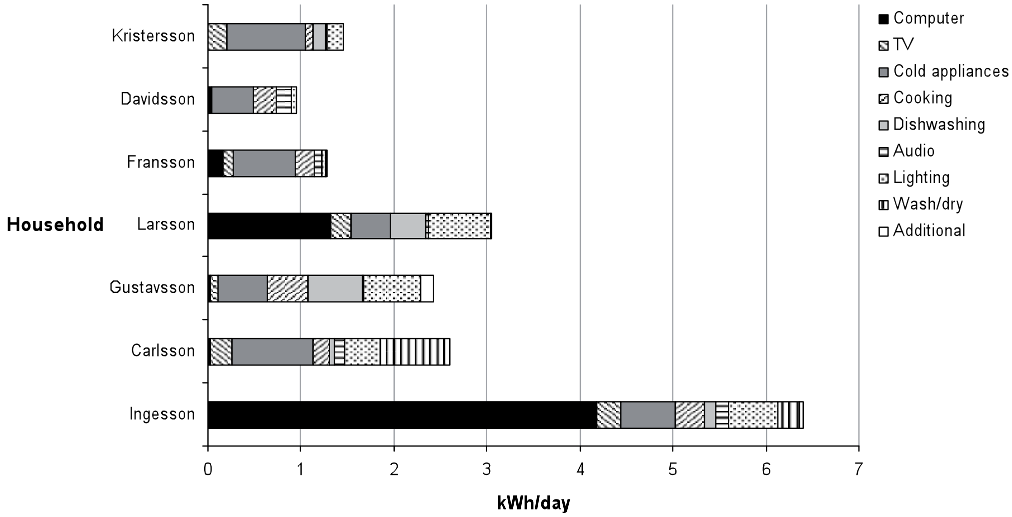

Figure 3. Electricity demand for different end-uses during the hours 9-17. Averages over the period May through July.

Table 4. Fraction of load for end uses during hours 9-17 (%), calculated over the period May through July. Large proportions are marked with boldface style.

Household	Comp.	TV	Cold app.	Cooking	Dishwash.	Audio	Lighting	Wash/dry	Add.
Ingesson	33	33	34	29	32	28	24	**79**	30
Carlsson	15	26	33	24	44	30	39	51	0
Gustavsson	30	21	35	26	36	43	25	10	20
Larsson	32	29	33	0	45	34	29	26	-
Fransson	37	30	34	50	-	33	21	**64**	29
Davidsson	39	2	33	**75**	-	31	9	-	-
Kristersson	50	38	33	25	50	35	39	-	25

a low and flat demand. Carlsson and Gustavsson have a considerably more variable demand with high morning or evening peaks. The most visible feature of the Ingesson and Larsson households is the high demand for computer use, contributing extensively to matching the PV profile. What underlies these features is discussed in the following, based on the interviews with the households. Much of this information can be found, together with extended discussions and analysis, in Karlsson & Widén (2008).

LOW-DEMAND HOUSEHOLDS

The three households with the lowest electricity demand, as seen in Figures 1 and 3, are rather similar both in the daily load distribution and the composition of daytime demand. Cold appliances form the single most energy-demanding appliance category, while the other loads cause visible but rather flat peaks at times of the day that differ somewhat between the households. Consequently, as seen in Table 2, these three households have the highest overproduction figures from the PV simulations.

The households follow the general trend of lower electricity demand in apartments, but the interviews also reveal more about how the households view their energy use. The man in the Fransson household claims to be actively engaged in lowering the energy use of the household, e.g. through avoiding standby or avoiding leaving lights on. In addition to this, he believes that his own use of miscellaneous appliances, such as TV and computer, is relatively low. He puts emphasis on energy savings:

"So I believe in a mix of developing new renewable sources and to lower the consumption of energy. That would be my recipe. And I have started also, so I believe my consumption is relatively low." (Karlsson & Widén, 2008, p.21)

In contrast to the claimed efforts of household Fransson to reduce consumption, the two other low-demand households do not present themselves as actively lowering their demand. Nonetheless, the Davidsson household, with the lowest electricity demand, does not have many electricity-demanding habits. Nor does the Kristersson household. With only a slightly higher electricity use than the Fransson household, which actively seeks to save energy, the Kristerssons' habits – like those of Davidsson – 'happen' to result in a relatively low consumption. For example, Kristersson have a pair of laptop computers but no Internet connection which results in relatively little use of computers at home. The TV use is actually higher compared to the other low-demand households, probably reflecting the Kristersson woman's claim of leaving the TV running in the background while performing other activities. Despite this, the household claims to use appliances efficiently on the whole, although the savings potential is not definite:

Interviewer: "But do you think you would be able to reduce your consumption?"

Man: “Yes, I sure think so. Everything is possible.”

Woman: “Well, we might, but I don’t know if I want to.” […]

Man: “No, it depends.”

Woman: “I don’t think we let [appliances] run unnecessarily.”

Man: “No, we don’t, oh no, if you only get to know for example how a fridge that is marked C or D performs compared to one that is marked A, well then you have a saving straight away.”

(Karlsson & Widén, 2008, pp.21–22)

Although the analysis is limited to these few households, it is worth noting that this is in line with the general finding that awareness and engagement for energy efficiency and environmental care is not uniquely linked to lower energy demand (Ellegård & Widén, 2006) or, at least, not a prerequisite for it.

MORNING AND EVENING PEAKS

The most visible feature of the Carlsson and Gustavsson households is the diurnal fluctuation of the electricity demand, with clear spikes in the morning and evening, respectively, and a much lower demand during daytime. These are the most unfavourable load profiles for direct matching with PV production of magnitudes similar to the load, since the demand is at its lowest when the PV output is at its highest. A more detailed inspection of the morning peak of Carlsson reveals that it is solely due to washing and drying. Washing and drying are also major components of the daytime demand of Carlsson as seen in Figure 3. In the interviews the woman in the household admits that she has a habit of washing often and non-efficiently:

Woman: “I guess I am a bit crazy about washing.”

Man: “Yes, it has to be done, right. But maybe it’s too often.”

Woman: “Yes. I don’t always wash with a full machine.”

Interviewer: “Yes. Okay.”

Man: “And you should.”

Woman: “But then I’ll have to wait.”

(Karlsson & Widén, 2008, p.50)

In the Gustavsson household, the high evening peak is predominantly due to cooking and dishwashing. A high fraction of dishwashing also occurs in the daytime demand in Figure 3. The household members are aware of a relatively high dishwasher use, claiming to run the dishwasher two to three times a day. They also explain that they prepare big dinners using various kitchen appliances. Often, different meals are also prepared in parallel because of special dietary requirements of one household member.

COMPUTERS AND STANDBY DAYTIME DEMAND

Daily fluctuations are also present in the Larsson and Ingesson households, but the most interesting features of these households are the relatively high daytime demands that make them the most well-matched apartment and detached house, respectively. In the Larsson household, the mean load curve in Figure 1 grows steadily from daytime through the afternoon and reaches a peak in the evening. In Ingesson the demand is rather constant on a level equal to the highest peak demands of the other households, with a slight peak in the middle of the day and a somewhat higher peak in the evening.

Inspection of the daytime demand in Figure 3 shows that roughly half of the Larsson demand and a major part of the Ingesson demand stem from computers. In Larsson the computers are said to be turned on when the two sons in the household come home in the afternoon – and as long as someone is at home the computers are running. The interviews also give a picture of constant conflicts around the computers:

Man: “There are conflicts. There are constant conflicts. You will have to book a time in advance and say that tomorrow at seven I want to use the computer. Well, maybe not really. But you have to say when you are having dinner that – boys, now I have to use a computer after dinner since I have to pay the bills or I have to check my mail or do this or that” (Karlsson & Widén, 2008, p.37).

The man reveals that the number of computers in the household resulted from the quarrelling – the parents bought one computer for each son to avoid conflicts between them. The activity patterns related to the computer use of the Larsson household are characterised by switching between active use of computers and so-called ‘process time’, when the computer is running in the background (Karlsson & Widén, 2008, p.38).

In the Ingesson household there are as many as six computers, including two servers that are running constantly. These computers are mainly used by the man in his work, which is performed from home. Privately, the man and wife claim they are hardly using computers at all. Strictly, the potential for load matching with PV thus arises not from household electricity but from professional activities. Another unrelated feature of Ingesson is washing and drying, which cause the mid-day rise in demand. This concentration of washing and drying to the middle of the day is also seen in Table 4.

Discussion

The base-case setups of 300 W_p and 540 W_p are well matched to the load. Producing at maximum a power equal to the coinciding load of a few household appliances, almost all produced electricity is consumed directly by the household, and the household is its own producer and consumer, interacting marginally with the grid. However, as the system sizes increase the households in practice become producers of solar electricity and to a lesser degree consumers of it – and this occurs at system sizes quite moderate compared to the total annual load. With net metering this is not a problem for the households, given that the production does not exceed the load of the billing period. However, from a grid point of view the overproduction may be critical when retrofitting large amounts of distributed generation into existing grids.

On the other hand, the variability of demand and matching between the households is evident and there are examples of daytime electricity use that is well-matched to the load. In some households washing and drying are by default scheduled to mid-day, as well as some cooking and dishwashing. In a few households the main part of the matching load was accounted for by standby or active-use electricity from computers, most notably in the household with home working. It is interesting that appliance loads that could be rather easily shifted, such as dishwashers and washing machines – since their operation requires little active use – are in many cases already well-matched to the PV generation. Washing can be expected to be scheduled to mid-day, at least in the summer, since clothes then can dry in the open air. It could be conjectured that households might become more aware of their own use of electricity through the installation of a small-scale PV system, or even alter daily activity patterns to increase load matching, but the degree of default matching of certain shiftable loads puts restrictions to the latter option. Also, as indicated by one household, environmental or energy-efficiency awareness does not necessarily correlate with different energy use than in households of comparable types and sizes.

Another aspect not possible to study in detail is the pattern of occupancy in the home and how this differs between households. However, it has been shown indirectly that higher daytime occupancy results in a higher degree of load matching. Occupancy is naturally one of the most important for the daily energy-use pattern since it is a prerequisite for most energy use, apart from standby electricity. Impacts of daytime occupancy are most clearly seen in the household where the man is working from home, which results in raised daytime demand. This suggests that, from a load-matching perspective, a large-scale introduction of PV should be directed towards areas with daytime occupancy.

Because of summer holidays the normal patterns of occupancy can be expected to be broken up – either resulting in lower or higher occupancy. It has not been possible to determine unambiguously from measurements nor from interviews the extent of this during the studied period. Nonetheless, as we have seen it has been possible to detect features of the quantitative patterns in the general picture of normal everyday activities given by the interviewees – but perhaps this correspondence would have been even clearer if an autumn period had been studied.

A concluding reflection is that domestic energy use and the factors determining it are complex and vary between households. One can rightly claim that every household is unique in this respect. This study has shown how some quantitative features determining the load-matching capability of individual household loads can be identified by qualitative analysis, thus showing the logic of the patterns in the context of the everyday life of the household members.

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