DANSK ENERGI

DEFU RAPPORT

Residential PV+Battery Load Profiles Suitable for Network Planning

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RESUME

The Danish Energy report “RA 595 – Part 2, Load profiles for dimensioning af low voltage networks; method for aggregation of load profiles” [*“RA 595- Del 2, Belastningsprofiler til dimensionering af lavspændingsnet, metode til aggregering af belastningsprofiler”*] describes how to create aggregated load profiles for use in the Net-Pro network planning tool. The report also documents load profiles of several types of residences, electric vehicles and PV. The PV+ST project has used simulation tools to predict how customers with both PV production and battery storage will react to various energy price and tariff scenarios. With small modifications, the method described in RA 595 for producing load/production profiles for varying numbers of PV+ST customers will be followed.

Unlike the other customer-types in Net-Pro, PV+ST customers are extremely flexible and can both consume, or produce power, depending on local circumstances (i.e. weather, spot-market prices). Thus, there are two separate “worst-case” scenarios for these customers: maximum production or maximum consumption in a given hour. The extent of flexibility of PV+ST customers is explored by simulating their optimal operation under 4 different tariff scenarios. If the network planners using Net-Pro are certain of the future tariff regime in their network, they can choose the load profile that best matches their situation. Alternatively, if the planners are uncertain of the structure of future tariffs, they can plan a network that is adequate in all tariff scenarios.

Profiles are produced for single customers, as well as aggregate profiles for 5, 10 and 20 customers. Profiles for 5 customers are recommended for use in all cases because this profile is similar to profiles for large numbers of customers, while accurately representing the few pioneer PV+ST customers initially expected in the coming years.

CONTENTS

CONCLUSION

The range between maximum production and maximum consumption of PV+ST customers is large under any given tariff scenario, and increases when variations in tariff regime are considered. This makes it costly to build distributions network that can handle the worst-case scenario of all tariff regimes. On the other hand, network planners have an opportunity to optimize infrastructure based on knowledge of long-term strategies about the tariff the regimes that will apply to network users.

Load profiles for summer and winter capture the seasonal extremes found in the consumption/production patterns. Separate profiles for weekend and weekdays were not produced because the quantity of simulation data was too small to create robust weekend profiles.

Profiles created for varying population sizes reveal little variation in profiles above a population size of 5. Considering that public networks with fewer than 5 PV+ST customers will see limited impact from this type of customer, it is recommended to use the profile created from aggregating 5 PV+ST customers when dimensioning low voltage networks.

These profiles represent optimal schedules, and assume perfect knowledge of future consumption, production, and energy prices. This is unachievable is practice, and it is not clear if practical limitations to the optimization will increase or decrease demand for network capacity.

INTRODUCTION

Fair tariffs reflect the actual cost of utilizing a network at a given place, at a given time. Done right, they will establish an equilibrium between the value network users gain from network capacity and the cost of providing that network capacity. Power-based tariffs are an important tool for fairly internalizing network costs. The motivation of this study was to show how power-based tariffs affect the optimal use of batteries in households with PV production.

METHOD

The profiles documented in this report are based on simulations. The simulations are initialized using measurements from smart meters, and assumptions about the behavior of customers in the future.

The smart meter measurements from a large Danish distribution utility were made available to the project, and 4 216 “prosumer” households with distributed generation (DG) were selected for further analysis. PV is the primary source of DG, but household wind power is also evident from the production profiles with injections at night. For the purposes of this study, it was assumed that all of these prosumers invested in identical battery storage systems (BSS) with the following specifications:

Battery Capacity	6 kWh
Battery Power	4.2 kW
Round trip efficiency	90 %

In the simulations, the measured loads of the prosumers is modified by controlling the BESS to minimize the total operations costs. The cost function includes energy costs in the day-ahead market, losses in the battery, and two types of network tariffs: volumetric tariffs (kr. / kWh) and capacity tariffs (kr. / kW). Battery losses are a function of battery utilization, prices in the day-ahead market in 2017 are used in the simulations. The level of network tariffs is modified in alternative scenarios that are compared in the analysis section.

Battery degradation is not modelled explicitly, however the round-trip efficiency is chosen intentionally to be lower than datasheet values, thus approximating the costs of battery wear-and-tear. Full documentation of the method used to solve the optimization problem can be found in *"A network-constrained rolling transactive energy model for EV aggregators participating in balancing market"* in the journal **IEEE Access**.

Tariff Scenarios

Four tariff scenarios are simulated to capture the full range of possible futures tariffs.

Scenario Name	Volumetric Tariff (DKK/kWh)	Capacity Tariff (DKK/kW per day)
Constant kWh	0.38	0
Time-differentiated kWh	0.32 (off-peak) 0.75 (peak[1])	0
KW low	0.08	1
KW high	0.08	5

Volumetric tariffs are only charged for energy purchase from the grid. Production from the prosumer does not incur volumetric tariffs. This is consistent with current practice. The scenarios with capacity tariffs include a relatively low volumetric tariff, which is set to the tariff the TSO charges all network users.

For optimization purposes, the cost of capacity tariffs are calculated based on the maximum power exchange with the grid during the optimization horizon (24-hours). Power tariffs are calculated for both consumption and production separately. Charging customers for their daily peak power is probably undesirable in practice, but for the purposes of optimization, it was infeasible to optimize power over multiple-day horizons.

The optimal operation of PV+ST prosumers is simulated during 30 days in winter (Jan. 1st – 30th) and summer (June 3rd – July 3rd). Data is grouped for each hour of the day in each season, and the measurements representing the 98 % and 2 % fractiles (highest production, highest consumption) are selected for creating two profiles for an individual PV+ST prosumer. Note that all days of a given season are grouped in the same category, weekends and holidays are not differentiated because limitations in the amount of simulation data did not produce enough data to create robust profiles of holiday consumption patterns.

AGGREGATED PROFILES

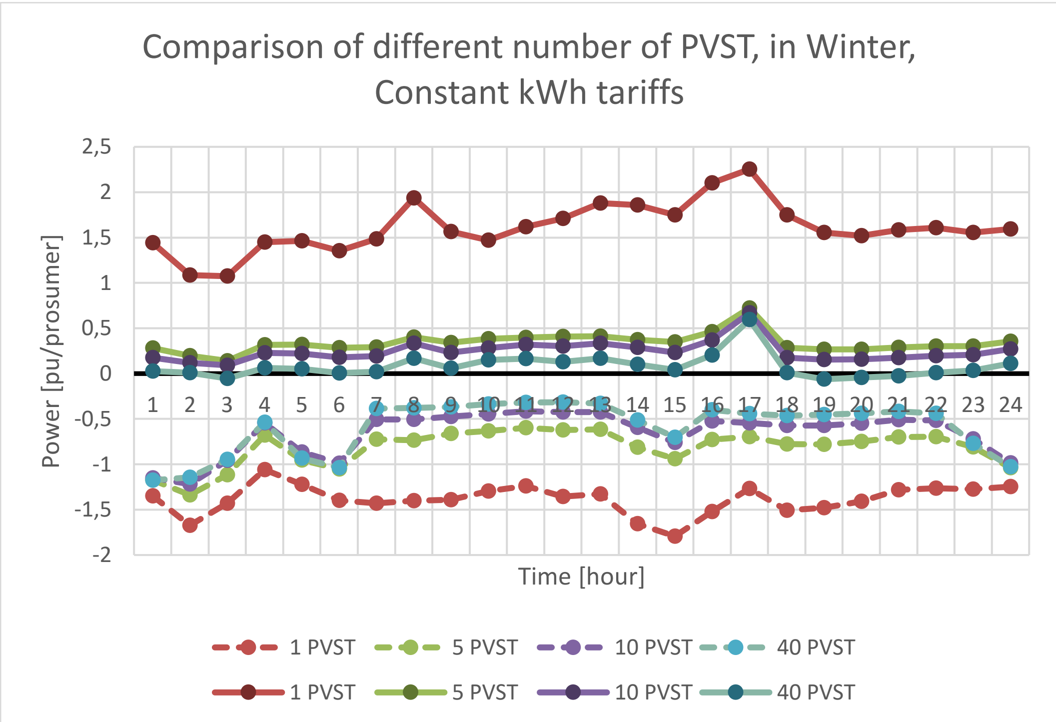
Profiles for groups of prosumer are not accurately represented by a summation of individual profiles because such a method does not account for coincidence. To account for the coincidence of loads, aggregate profiles were generated for 5, 10, and 40 prosumers.

These profiles were generated by randomly selecting **N** individual prosumer timeseries, and adding them together to create a simple sum of the sampled prosumers. This was done 250 times, to create a population of N-prosumers. From this population, for each hour, in each season the 98 % and 2 % fractiles of maximum and minimum load are selected to create two profiles for N PV+ST customers.

[1] Peak tariffs apply from 17:00 – 19:59 during winter.

Aggregated Profiles: 5, 10 and 40 prosumers

The aggregated simulation profiles show that there is large difference between profiles for one prosumer and aggregations of several prosumers, which is expected. What is surprising is how little difference there is between 5 and 40 prosumers. This can be explained by fact that parameters in the optimization, such as energy prices and solar radiation, are identical for all prosumers, the primary variable in input is the households own domestic consumption. Domestic consumption appears to have magnitude that is small compared to the capacity of the batteries. The similarity of profiles with more than 5 prosumers indicates that further analysis of the simulation profiles are not strongly sensitive to the number prosumers aggregated together, as shown in the figure below.

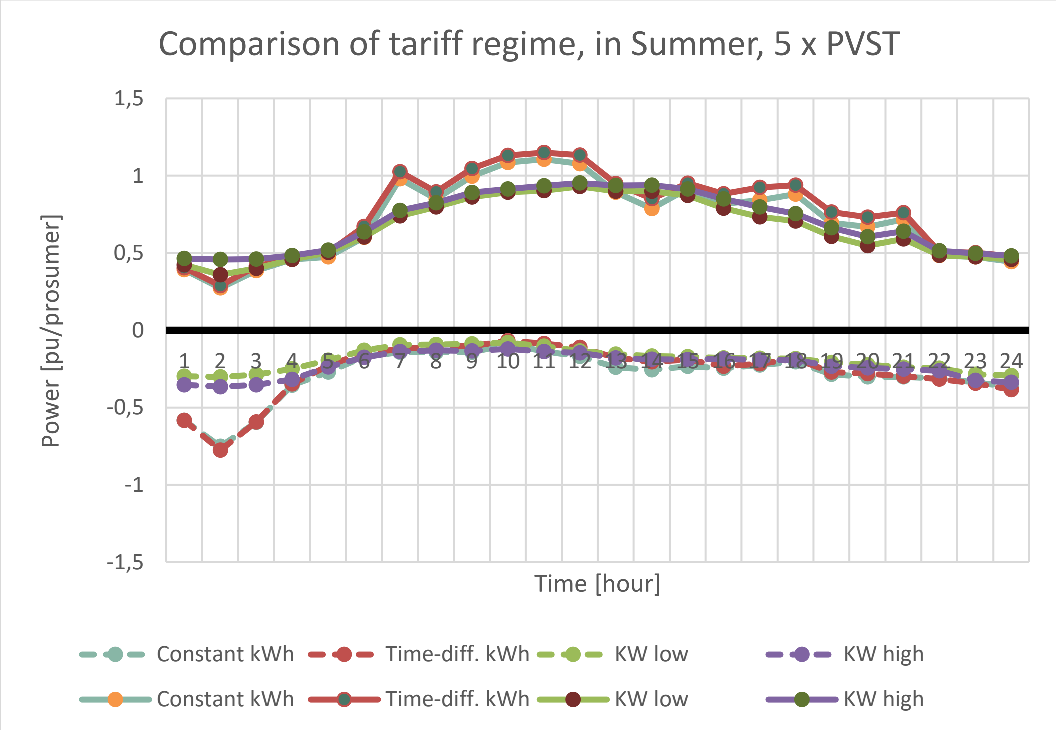


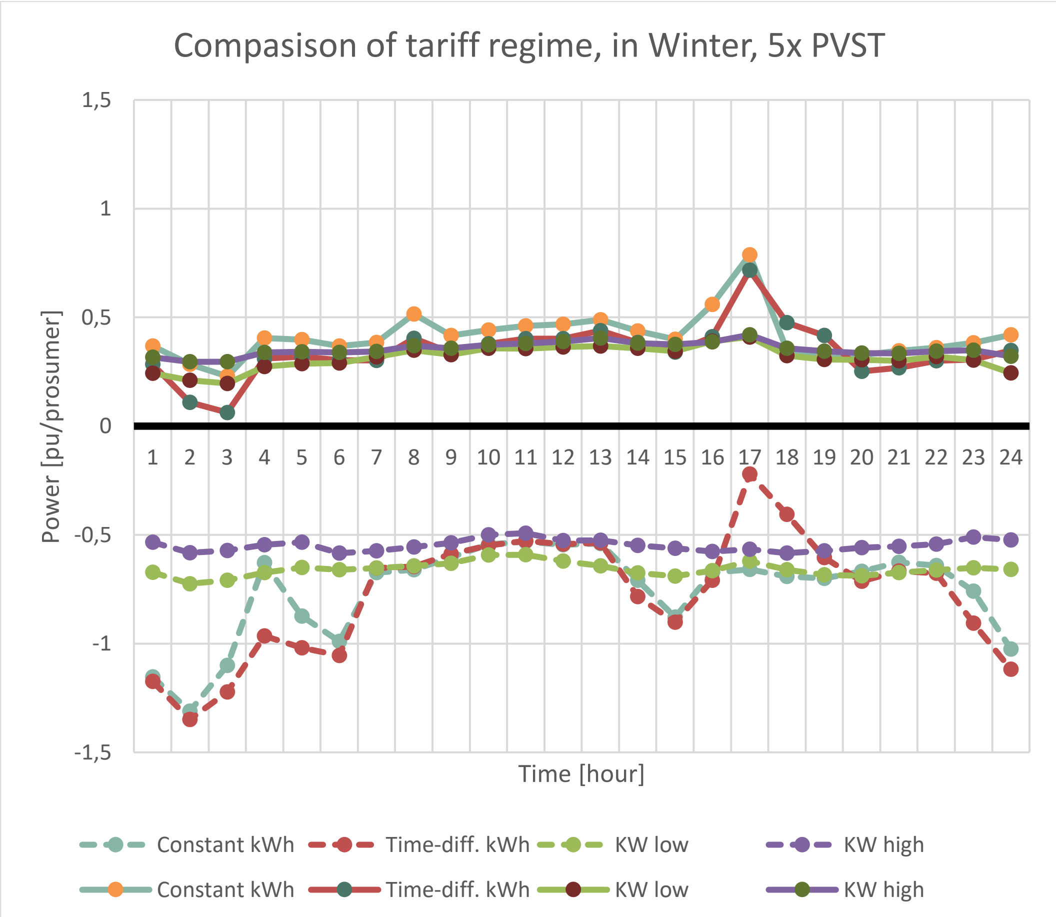
[Note that in the figure negative values imply consumption, and positive values production. The y-axis units are per unit of a prosumers rated battery power, in this case 4.2 kW]

Considering this, and considering that these profiles are intended for planning studies for the initial rollout of BESS in LV distribution systems, profiles of 5 prosumers are used in the analysis that follows.

Tariff Regime

Considering the effect of alternative tariffs, it can be seen that the profiles that result from optimizing the 2 types of volumetric tariffs resemble each other, and the profiles optimized for two levels of capacity tariffs also show a strong degree of similarity.


Comparison of tariff regime, in Summer, 5 x PVST
Power [pu/prosumer]
1,5
1
0,5
0
-0,5
-1
-1,5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time [hour]
Constant kWh
Time-diff. kWh
KW low
KW high
Constant kWh
Time-diff. kWh
KW low
KW high


Compasison of tariff regime, in Winter, 5x PVST
Power [pu/prosumer]
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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time [hour]
Constant kWh
Time-diff. kWh
KW low
KW high
Constant kWh
Time-diff. kWh
KW low
KW high

The summer profiles of both types of volumetric tariffs are actually identical, because the peak tariff only applies in winter. The winter profiles of the volumetric tariffs show that the peak tariff reduces consumption during peak hours and increases consumption in the late night; production, which is not charged volumetric tariffs, is mostly unchanged.

Compared to scenarios with volumetric tariffs, capacity tariffs flatten load and production profiles, as expected. The difference between a the low- and high-tariff scenarios are less distinct, even though the difference in capacity price was large (5 times). This indicates that there are greatly diminishing returns, and higher costs, associated with aggressively pursuing an optimization strategy that limits peak capacity usage. Also, notice that during peak hours, load is higher, and production is lower when using capacity tariffs, compared to volumetric tariffs. Even constant kWh scenario, without peak volumetric tariffs, the price signal from the DAM motivates aggressive use of the battery to deliver power during peak times (which are also high-price times). At the price levels simulated, the capacity tariff dampens this DAM price signal. This has implications during the transition from today's passive consumers to tomorrow's active prosumers. Someday prosumers may synchronize their use of the distribution grid to create new bottlenecks, but at present, there is a strong correlation between high network load and high prices, which aligns the interests of the network operator and prosumer when using volumetric tariffs.

RAW DATA OF SIMULATION PROFILES

The following tables are inserted as embedded Excel spreadsheet objects, to facilitate future use of the data. The units of the tables are power production (consumption is negative) per customer relative to the rated power of the battery. To convert to units of kWh per customer, multiply the figures by the rated battery power, 4.2 kW. Production above rated power indicates that the prosumers' DG is injecting power.

"Comparison of different number of PVST, in Winter, Constant kWh tariffs"

Hour of the da	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Winter - Load																								
1 PVST	-1.34921	-1.67214	-1.42857	-1.05952	-1.22143	-1.39762	-1.42857	-1.4	-1.39048	-1.29524	-1.2381	-1.35476	-1.32619	-1.65714	-1.79286	-1.52143	-1.26905	-1.50905	-1.47857	-1.40714	-1.28095	-1.26429	-1.27619	-1.24524
5 PVST	-1.17048	-1.33792	-1.11429	-0.67905	-0.95269	-1.05333	-0.72476	-0.734	-0.6619	-0.63127	-0.5981	-0.62016	-0.61429	-0.81135	-0.94	-0.72667	-0.69714	-0.77857	-0.77967	-0.74714	-0.69857	-0.69476	-0.8091	-1.03857
10 PVST	-1.14929	-1.21828	-0.95603	-0.54404	-0.86508	-0.98857	-0.50476	-0.50476	-0.47524	-0.44443	-0.41524	-0.42352	-0.42564	-0.59189	-0.76	-0.52262	-0.54593	-0.57071	-0.57353	-0.54643	-0.50881	-0.5165	-0.7201	-0.98348
40 PVST	-1.17564	-1.14559	-0.94761	-0.5387	-0.93221	-1.0379	-0.38482	-0.3783	-0.36758	-0.33579	-0.31963	-0.3158	-0.32994	-0.51267	-0.70163	-0.39802	-0.44057	-0.46458	-0.45131	-0.43679	-0.41748	-0.43695	-0.76845	-1.02655
Winter - Production																								
1 PVST	1.443651	1.085714	1.07381	1.45	1.461905	1.354762	1.483333	1.935714	1.564286	1.469048	1.619048	1.711905	1.878571	1.857143	1.75	2.1	2.252381	1.75	1.554762	1.519048	1.583333	1.607143	1.554762	1.595238
5 PVST	0.281429	0.195503	0.140952	0.315714	0.32	0.285476	0.292714	0.401429	0.342	0.385238	0.397619	0.407143	0.412857	0.371905	0.347143	0.461905	0.722538	0.28619	0.267619	0.266587	0.288095	0.302857	0.303143	0.355238
10 PVST	0.174497	0.117405	0.091667	0.230043	0.220476	0.179762	0.192857	0.334881	0.231333	0.281619	0.319841	0.30381	0.334286	0.289127	0.230238	0.370952	0.667857	0.175	0.153333	0.158786	0.174762	0.195571	0.20834	0.270095
40 PVST	0.025738	0.008394	-0.05232	0.060949	0.052339	0.005012	0.020173	0.169542	0.060107	0.151304	0.164808	0.129615	0.168083	0.101488	0.0415	0.202143	0.59424	0.00956	-0.06222	-0.04228	-0.02633	0.008982	0.035282	0.1114

“Comparison of tariff regime, in Summer, 5 x PVST”

	Summer	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Load	Constant l	-0.5836	-0.75138	-0.59624	-0.35476	-0.27095	-0.17095	-0.14257	-0.14143	-0.14286	-0.09164	-0.13619	-0.1681	-0.23905	-0.25555	-0.23229	-0.24524	-0.22571	-0.20333	-0.28571	-0.3019	-0.30048	-0.31095	-0.33619	-0.36857
	Time-diff.	-0.58381	-0.77572	-0.59376	-0.3461	-0.22905	-0.14429	-0.1241	-0.1	-0.10333	-0.06652	-0.08571	-0.11079	-0.17619	-0.20381	-0.18986	-0.23286	-0.21714	-0.18603	-0.27048	-0.28095	-0.29667	-0.31523	-0.34333	-0.38429
	KW low	-0.29752	-0.30195	-0.28762	-0.24972	-0.19354	-0.1297	-0.09367	-0.09226	-0.08872	-0.08027	-0.1024	-0.13354	-0.15473	-0.16643	-0.17042	-0.17886	-0.18076	-0.18375	-0.20753	-0.22359	-0.23834	-0.24625	-0.28491	-0.29408
	KW high	-0.35269	-0.36476	-0.35266	-0.31715	-0.23821	-0.17581	-0.138	-0.13021	-0.13349	-0.12028	-0.1381	-0.14567	-0.1788	-0.18805	-0.1893	-0.18587	-0.19206	-0.19239	-0.23354	-0.24419	-0.2521	-0.26246	-0.32454	-0.33602
Prod.	Constant l	0.392381	0.273333	0.386238	0.457619	0.475238	0.601429	0.980143	0.850476	0.995714	1.085238	1.106667	1.078095	0.892698	0.787937	0.91619	0.817619	0.842333	0.880905	0.69381	0.669048	0.717619	0.483667	0.475238	0.444762
	Time-diff.	0.40381	0.289048	0.412381	0.469571	0.50381	0.672381	1.025714	0.894286	1.045238	1.131111	1.149101	1.132963	0.95	0.852381	0.951429	0.883333	0.924762	0.937683	0.764762	0.731429	0.76	0.508095	0.502381	0.479048
	KW low	0.422705	0.359247	0.399362	0.457873	0.504116	0.602821	0.739078	0.797878	0.862625	0.892963	0.90418	0.930754	0.899996	0.89842	0.871709	0.790185	0.733651	0.70741	0.607914	0.547562	0.591607	0.485258	0.475015	0.458918
	KW high	0.465521	0.457632	0.459888	0.483581	0.518123	0.636968	0.775798	0.82455	0.890742	0.912743	0.934964	0.952261	0.93733	0.938562	0.913968	0.849912	0.798837	0.754981	0.66267	0.605975	0.640834	0.514083	0.49723	0.480875

“Comparison of tariff regime, in Winter, 5 x PVST”

	Winter	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Load	Constant l	-1.15381	-1.31048	-1.10048	-0.62857	-0.87333	-0.99048	-0.67381	-0.66014	-0.60333	-0.54381	-0.53103	-0.54619	-0.53905	-0.70952	-0.87857	-0.67286	-0.65907	-0.69175	-0.69986	-0.66714	-0.62714	-0.64048	-0.75926	-1.0255
	Time-diff.	-1.17317	-1.34857	-1.2219	-0.96534	-1.01942	-1.05482	-0.65286	-0.64524	-0.58857	-0.54857	-0.52762	-0.54238	-0.53714	-0.78398	-0.90209	-0.70952	-0.22	-0.40571	-0.6049	-0.71333	-0.66619	-0.67662	-0.90598	-1.11804
	KW low	-0.67184	-0.72448	-0.70886	-0.67315	-0.65067	-0.66021	-0.65331	-0.64324	-0.63072	-0.59226	-0.59155	-0.62078	-0.64247	-0.67486	-0.68955	-0.66531	-0.62105	-0.66096	-0.68442	-0.68867	-0.67304	-0.66153	-0.65143	-0.65808
	KW high	-0.53359	-0.58193	-0.5721	-0.54527	-0.53358	-0.58434	-0.57337	-0.55556	-0.53688	-0.49936	-0.4921	-0.52576	-0.52474	-0.54795	-0.56151	-0.57634	-0.56613	-0.58346	-0.57292	-0.55917	-0.55225	-0.54251	-0.50948	-0.52367
Prod	Constant l	0.368571	0.284762	0.229312	0.405714	0.398095	0.368095	0.384286	0.514762	0.41619	0.441667	0.460952	0.469048	0.488571	0.437143	0.398624	0.56	0.787619	0.35	0.328095	0.327143	0.345714	0.361429	0.383333	0.419333
	Time-diff.	0.284286	0.108757	0.062857	0.311429	0.32	0.30319	0.301905	0.40381	0.337571	0.378714	0.401905	0.402857	0.439524	0.384762	0.340952	0.411429	0.716667	0.47619	0.416667	0.251619	0.267619	0.300952	0.30619	0.348095
	KW low	0.242666	0.211471	0.196516	0.274309	0.287725	0.290842	0.317701	0.349384	0.327865	0.358108	0.356852	0.363349	0.369002	0.357529	0.344578	0.391053	0.410179	0.324799	0.306372	0.304637	0.300618	0.319852	0.303783	0.245163
	KW high	0.316858	0.295537	0.296591	0.339007	0.34163	0.339188	0.3427	0.36935	0.357355	0.373441	0.38077	0.389487	0.405512	0.382125	0.375634	0.387538	0.420072	0.358594	0.344113	0.335767	0.334396	0.344408	0.348636	0.320752

APPENDIKS 1 IMPLEMENTATION IN NET-PRO

An implementation of the PV+ST profiles was attempted in Net-Pro, but had to be abandoned. Net-Pro is a tool created from an Excel spreadsheet, and an series of macros. The history of this tool stretches back to the previous century (1998), and over time, the implementation has become inflexible with respect to adding new features. Accommodating the duel nature of PV+ST as both consumers and producers of energy required a major restructuring of the tool. The nature of such a complex spreadsheet, with ample cross-references and macros, resulted in unpredictable side-effects of incremental changes to the structure. It did not help, than some of the functions used by the spreadsheet have become deprecated, and unstable.

Manpower scarcity also influenced the decision to cease this development effort; the colleague responsible for the program choose to end his employment at Dansk Energy at a critical time.

Therefore, this report is written as a reference to future developers of planning tools, so that they can integrate the findings of this research into their network dimensioning algorithms.

A spreadsheet with the raw data used to produce the figures accompanies this report.