Solar Skyways

Conditions for a Personal Rapid Transit (PRT) System in Uppsala

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Abstract

This report examines the possibilities of building the planned Personal rapid transport (PRT) system in Uppsala city and operating it on solar energy from PV modules mounted on the tracks roof. Using technical specifications from producers and developers, simulation programs such as Arena, PVsyst and Matlab were used to calculate power consumption and production. Further calculations were done in Matlab to investigate the possibility of connecting energy storage to the PRT system.

The result is that a PRT system with photovoltaics, without associated energy storage is the most interesting solution for a city like Uppsala. The profitability of the PVs depends on the future electricity prices. For a municipality, such as Uppsala, there may however be other incentives in addition to the economic, which also motivates PVs attached to the PRT tracks.

Sammanfattning

Denna rapport syftar till att undersöka möjligheterna att göra den planerade spårtaxibanan i Uppsala driven av solenergi, med utgångspunkt att solcellerna ska vara monterade på spårbanans ovansida. Med hjälp av tekniska specifikationer från tillverkare och utvecklare av spårbanor har simuleringsprogrammen Arena, PVsyst och MatLab använts för att räkna fram energiförbrukning och elproduktion för spårbanan i Uppsala. Det har även gjorts beräkningar i MatLab för att undersöka de ekonomiska möjligheter som finns för att koppla ett energilager till systemet.

Resultatet är att en spårtaxibana med solceller utan tillhörande energilager är mest intressant för en stad som Uppsala. Angående solcellerna så hänger mycket av lönsamheten på framtidens elpriser. För en kommun som Uppsala kan det dock finnas andra incitament utöver de ekonomiska, som också motiverar solceller kopplade till spårtaxibanan.

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Introduction

Background

Constantly increasing concerns regarding rapid anthropogenic global warming require immediate attention, and drastic changes are required in order to address the problem. Transports are a large contributor to carbon dioxide emissions, and a composed conversion within the transportation sector, away from vehicles powered by fossil fuels, towards public transports, driven by renewable energy sources, may play a dominant role in solving the alarming traffic situation in Uppsala, shadowed by rising levels of city pollution and heavy fines. Public transportation has many advantages over cars, such as lowering CO_2 emissions, reducing traffic jams and providing a more efficient option of transportation, and in the on-going shift away from fossil fuels, alternative solutions for transportation are being investigated by Uppsala municipality. It has been proposed to replace buses, the core of public transportation in Uppsala, with vehicles powered by renewable energy sources such as biogas or green sources of electricity. One of the more favourable solutions involves the construction of an electrical track bounded system (WWF 2013); more specifically, the design of a public personal rapid transit transportation system, which, according to the authors, would be well dimensioned for a city of Uppsala's size.

Personal Rapid Transit

Personal rapid transit (PRT) is a public transport system featuring small track bounded vehicles which, similar to taxis without drivers, travel to passenger-selected destinations. The main concept of PRT is that public transport can be individually adapted to an extent comparable to private car journeys. The PRT vehicles have no fixed routes and instead, passengers determine which stations the podcar will stop at.

The Situation in Uppsala

Sweden has previously received heavy fines by the European Union (EU) since several municipalities have failed to meet the standards of air pollution in larger cities. Uppsala is one of the involved municipalities and constant measures are systematically taken in order to increase air quality in the inner city. Despite attempts to deal with pollutant levels, the problem yet remains and heavy fines once again threaten Sweden (Dagens Nyheter 2013).

The Uppsala municipality has planned to build a PRT from Uppsala Travel Centre to Uppsala Biomedical Centre, passing both the University Hospital and Uppsala Science Park, roughly a 3,8 kilometre route. Feasibility studies have been made (Uppsala Kommun 2011) and a self-evident benefit of the PRT system would be a reduced consumption of fossil fuels in Uppsala city, since the system will be run on electricity. This would result in both lower carbon dioxide emissions and better inner city air. The International Institute of Sustainable Transportation (INIST) is an association with the common interest of building a PRT system in Uppsala, and additionally, investigating the possibilities of powering the transportation system on solar energy.

Purpose

The purpose of this report is to investigate the possibilities of powering the planned PRT system in Uppsala by solar energy.

Problem Statements

In regard to the purpose of this report, the following problem statements have been set:

- How much electricity will the PRT system consume?
- How much electricity can be produced with photovoltaic (PV) modules on top of the PRT track and station roofs?
- What pros and cons are associated with having an energy storage system?
- Economic calculations concerning the PV system, energy storage, grid connection and electricity sales/buys.

Client and Supervisor

Christer Lindström and Ron Swanson at INIST have initiated this project. Joakim Widén at Uppsala University has been supervising the progress.

Previous Research

On behalf of Uppsala city, the Institute for Sustainable Transportation (IST) made a report in 2011 on how a PRT system in Uppsala could be built. The route mentioned in the report begins at the Travel Centre, passes by the football arena "Studenternas", loops around the Universal hospital, passes by Science Park and ends at the Biomedical Centre. The total length of the track is 3,8 kilometres, it is assumed to have ten stations and the planned route is shown in Figure 3. (Hunhammar, Lindström 2011)

The podcars will be hanging beneath the rail and therefore PV modules can be mounted on top of the track. Figure 1 below, shows a computer-generated picture of what a similar system may look like.

Figure 1: Concept picture of what a PRT system with hanging podcars may look like. (Beamways 2008)

Report Outline

The structured of the report is divided into three major chapters; firstly regarding the PRT's energy consumption, secondly concerning the PV modules energy production and finally the possibilities of energy storage. The work behind each of these chapters is closer explained under respective captions below.

Three different scenarios were investigated:

- Criterion for scenario A is that the PRT system is self-sufficient on in-house solar power on an annual basis.
- In scenario B the podcars have an increased energy consumption by 50%, and again the criteria is to be self-sufficient on in-house solar power on an annual basis.
- In scenario C, criteria are for the PRT system to be self-sufficient on in-house solar power from April to August.

Scenario A is the main scenario and has therefore been prioritized. Scenario B was done to demonstrate how large portion of additional solar electricity production was required if the podcars were more energy consuming. The main purpose of scenario C was to investigate the economic impact of a more downscaled PV system, not self-sufficient on an annual basis, and with reduced overproduction of energy during summer months. This system design could be of greater relevance for countries with higher and more evenly distributed solar insolation levels, since it may then also be self-sufficient. In scenario A and B, considerable amounts of electricity are over-produced and sold to the city grid during summer time, and in winter, electricity is re-purchased instead.

This report is based on several sub-reports, and for the sake of clarity, the reports have been divided into the three major areas of interest, according to Table 1 below.

Table 1: List over sub-reports.

Area of Interest	Sub-report no.	Name of sub-report
Conditions	X11	Travel Patterns Estimation
Conditions	X12	Placement of Modules
Electricity production and consumption	X21	Photovoltaics and Converters
Electricity production and consumption	X22	Travel Simulations in Arena
Electricity production and consumption	X23	Production Simulation in PVSyst
Energy storage, regulation and the city grid	X31	Energy Storage
Energy storage, regulation and the city grid	X32	Electrical Grid Requirements

Method

Electricity Consumption

The energy consumption of the PRT system was calculated via parameters retrieved from the simulation software Arena. However, in order to calculate the energy consumption of the PRT system in operation, estimations regarding travel patterns in Uppsala had to be made.

Travel Estimations

Traveller counts on the bus services between the central station (Uppsala Central Station), the city hospital (Uppsala University Hospital), Uppsala Science Park and Uppsala Biomedical Centre (BMC) were done to estimate the number of travellers on the planned PRT route today. Together with these counts, the number of employees and students, active along the different parts of the route was taken in mind to decide to which stations the travellers are travelling. Additional travellers were also added, to account for people transferring from car travel to PRT commuting. The aim of this study is to estimate the traveller flows during a typical day.

Modelling in Arena

In order to obtain a credible model of the PRT system, the simulation software Arena was used. Parameters and data attained from travel estimations were used in the model in order to estimate the amount of podcars required to meet system demands, and the energy consumption of the PRT system in operation. Three different types of days were created; normal weekday, weekend day and vacation day, and a plausible combination of these day types were then merged into a full year. Finally, two different scenarios were simulated: The case of standard consumption, where the podcars power requirements are similar to that of the vehicles in the already active PRT system in Heathrow, London, and a high consumption scenario, where the power demand of a driving podcar is increased by 50% from the standard case.

Electricity Production

Modelling in PVsyst

PVsyst is a simulation software, equipped with functions enabling practical design and data analysis of PV systems. In order to reach designated production of the PV system, multiple simulations were done in PVsyst. By using the planned route in Introduction of PRT in Uppsala (Hunhammar, Lindström 2011), Eniro and Google maps, and also in real life measurements, a downscaled model was designed in the software. Different segments of the pod car track were simulated separately in smaller sub-models in order to determine their productivity and relevance to the system. A section of the sub-model “Strandbodgatan” is shown in Figure 2 below.

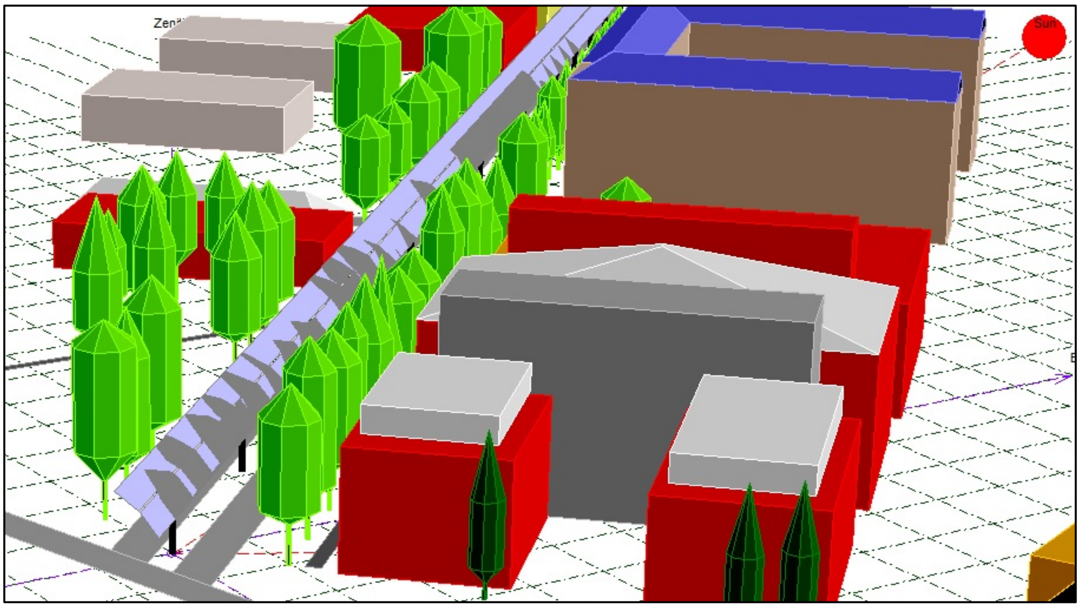

Figure 2: Model over Strandbodgatan made in PVsyst.

Three different energy production scenarios (A, B and C), as previously mentioned in the report outline, were summarized in a comparison to illustrate alternatives when designing the PV system. The efficiency from inverter output was assumed to be 90 %; hence system production exceeding the calculated consumption of the PRT system. Simulations were done for each productive segment of the system and then summarized to illustrate the total production of the system for each scenario, every hour of the year. The most productive parts of each system were chosen in regard to orientation and shading losses. The eleven productive segments of the track are listed and shown in table 2 and the locations of the segments are shown in Figure 3.

Table 2: Segments of the PRT track used in each scenario.

Number	Distance [m]	Capacity*	Name	Scenario (A)	Scenario (B)	Scenario (C)
1	425	430	Railway	x	x	x
2	495	504	Strandbodgatan		x	
3	144	147	Östra Ågatan	x	x	
4	316	320	Studenternas	x	x	x
5	125	126	Akademiska Sjukhuset	x	x	
6	90	90	Akademiska Sjukhuset	x	x	x
7	80	80	Akademiska Sjukhuset	x	x	x
8	240	242	Akademiska Sjukhuset	x/2**	x	
9	60	60	Akademiska Sjukhuset	x	x	x
10	60	60	Science Park	x	x	
11	60	60	Science Park	x	x	x
12	-	302	Station Roofs	x	x	
Total	**2095**	**2420**		**1670**	**2420**	**1040**

*Installed capacity used in PVsyst-simulations. **Half of segment used

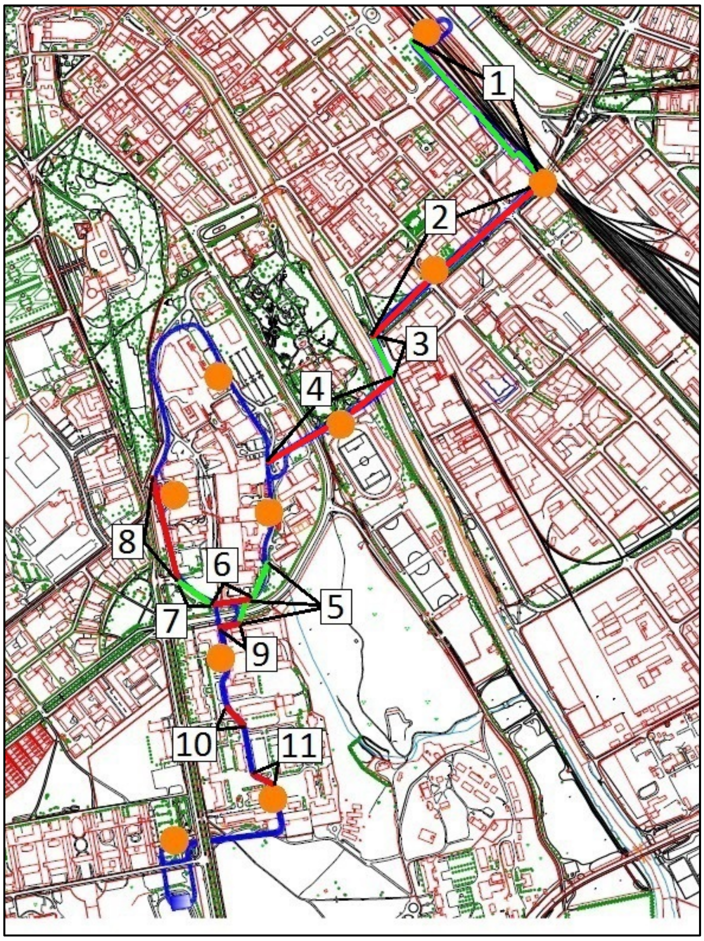

Figure 3: Planned route of PRT system divided inte segments. (Hunhammar, Lindström 2011)

More profound results are presented in the Results section in the report. For detailed estimations, calculations, choice of components, scenario details, dimensioning of PV modules, production and losses, see sub-report X23 - Dimensioning the Photovoltaic System.

Energy Storage

As an electricity distributer via the city grid, electricity utility based on the burden of power output must be paid for. A PV system is an intermittent energy source, and it is nearly impossible to predict the exact power output generated by the modules at a given time. By utilizing in-house energy storage, it is possible to ease high power output to the city grid, and thereby reduce costs. As presented in sub-report X31 - Energy storage, storage by batteries is assumed to be the most viable solution for this project, due to system prerequisites and requirements.

Simulation in Matlab

In order to simulate a clever battery for energy storage, programming was done in MatLab. The code was built from a small battery simulation code, constructed by Joakim Widén. Energy storage enables the system to utilize produced electricity at later hours, which in turn, reduces grid costs for buying and selling power. Additionally, in order to further reduce electricity purchases when power costs are highest, a control system was designed to ensure that the battery was sufficiently charged in preparation for upcoming peak-load hours.

Economic Calculations

In each sub-report, minor economical calculations regarding investments and operational costs were made, and are presented in the results section below. The costs of building the PRT system has not been taken into consideration, however, earlier reports estimate this cost to approximately 650 MSEK (Hunhammar, Lindström 2011).

Results

The PRT system will run on 750 V DC power supply and be connected to the high voltage city grid of Uppsala, 50-30 MVA, 11-20 kV AC. This will be the PRT track's main supply source of steady power. The electricity produced by the PV system will be transformed into 400 V AC and provide electricity for low voltage internal consumption by regulators, lighting at the stations and so forth. The excess electricity will primarily be used to supply the PRT track with 750 V DC, and then be fed into the main low voltage city grid of Uppsala.

The entire system, including the PRT track, station houses, PV modules, energy storage and connections to the electrical grids, is shown in Figure 4 on page 10. Detailed estimations and evident reasoning behind choice of components and system design can be found in sub-report X21 – Photovoltaics and Converters. Installed PV rated power and annual values for electricity consumption and production can be found in table 3 on page 11.

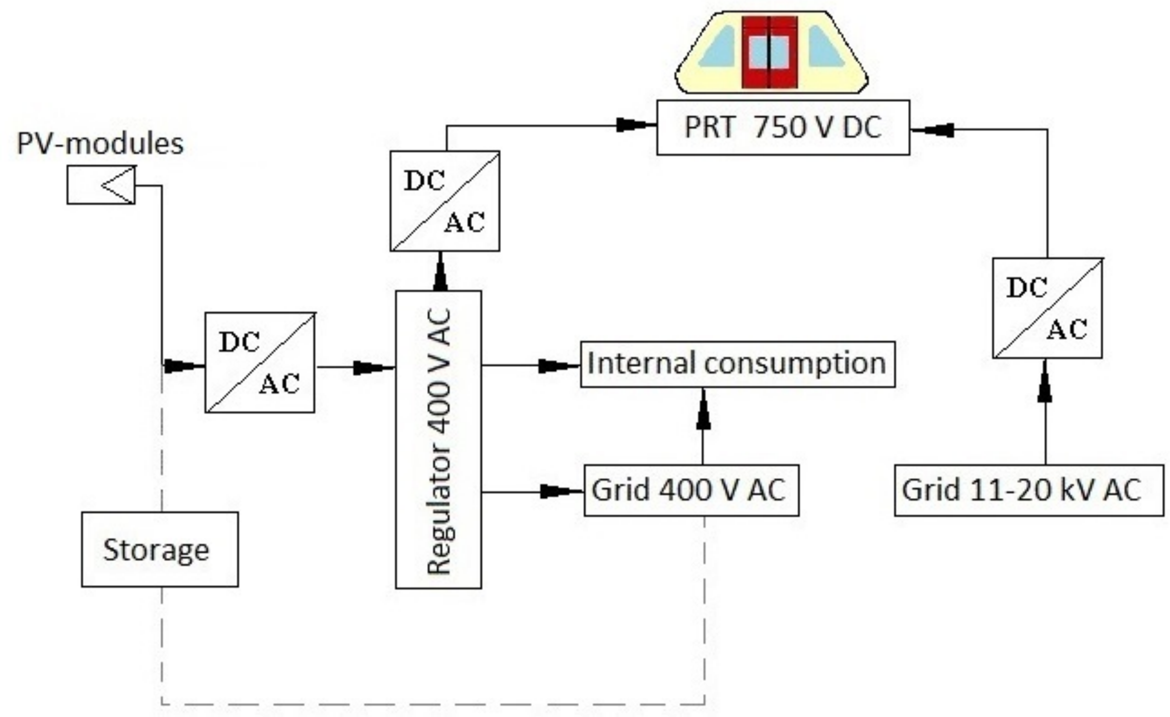

Figure 4: Sketch over the PRT system and how it is connected to electrical grids, the PV modules and the energy storage.

Travel Estimations

The travel patterns below, in the Figures 5 and 6, are based on empirical studies of the travellers on buses, today occupying approximately the same route as the future PRT system. The figures illustrate estimated travel patterns for travellers southbound and northbound in the planned PRT system, and it is assumed that the two graphs are in regard to the travel patterns for the whole system during a regular weekday. For a more profound understanding regarding travel patterns and how these results were attained, detailed estimations and calculations are fully explained in sub-report X11 – Travel patterns estimation.

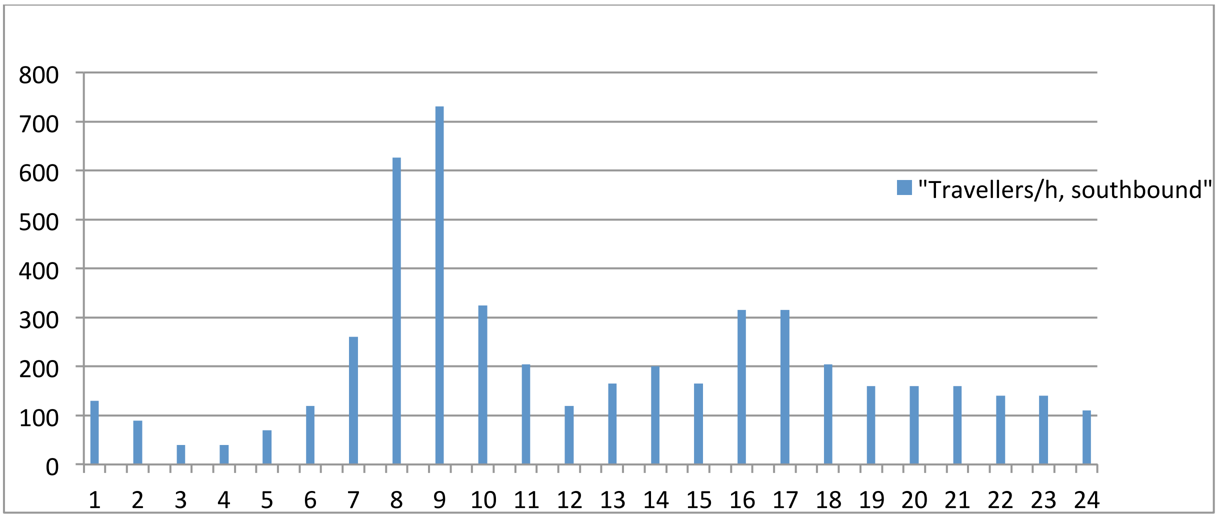

Figure 5: Shows the estimated travel patterns for southbound travellers per hour.

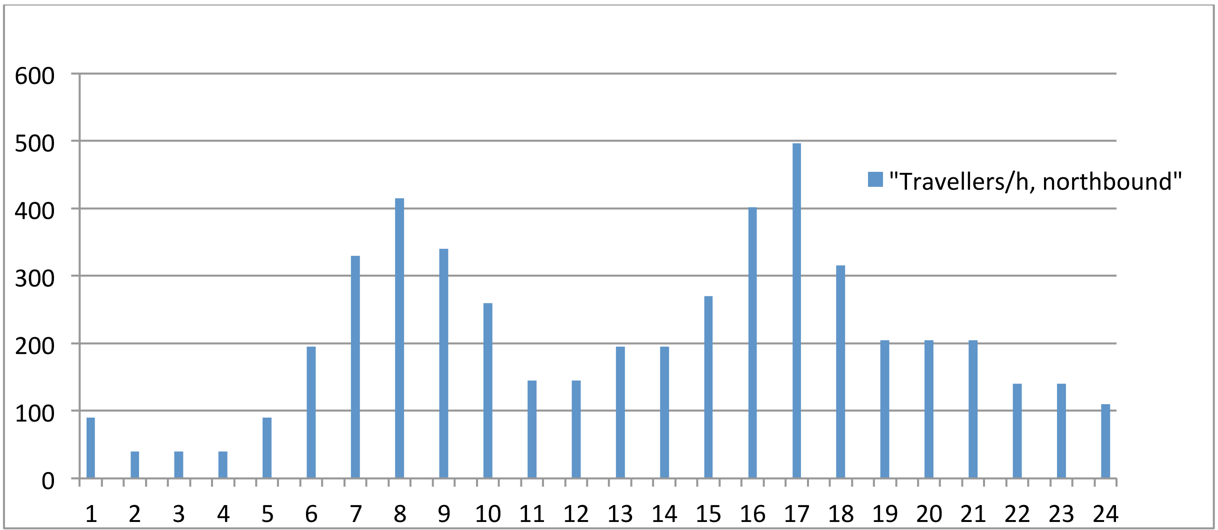

Figure 6: Shows the estimated travel patterns for northbound travellers per hour.

Energy consumption

Below, Figures 7 and 8 show the average hourly power consumption of the modelled PRT system, simulated in Arena. Detailed estimations and calculations can be found in sub-report X22 – Travel simulation in Arena.

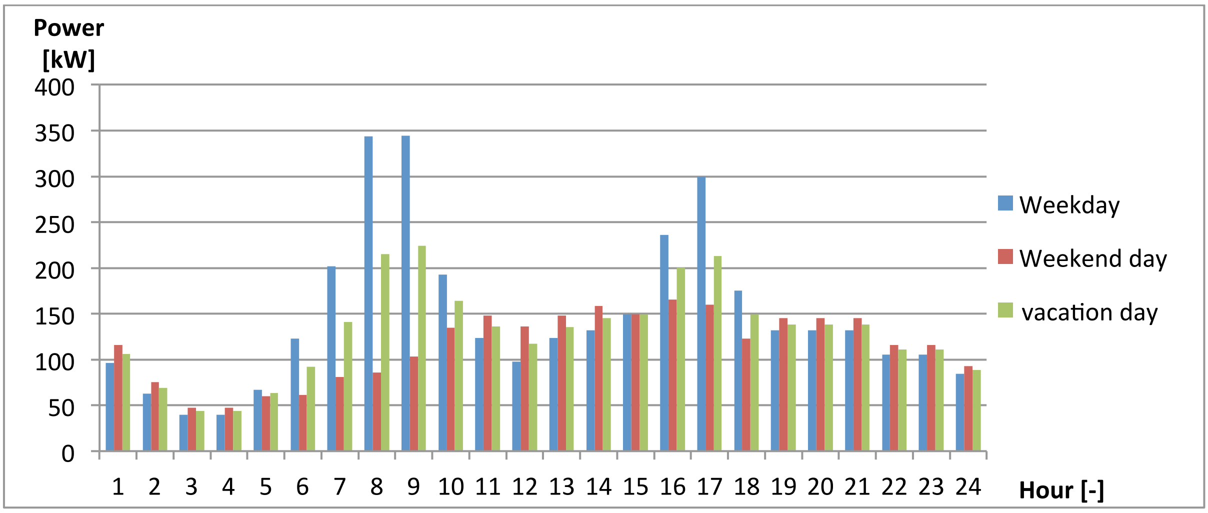

Figure 7: Average hourly power consumption in the PRT system simulated in Arena. The pod cars power consumption is estimated to be about the same as the pod cars at Heathrow.

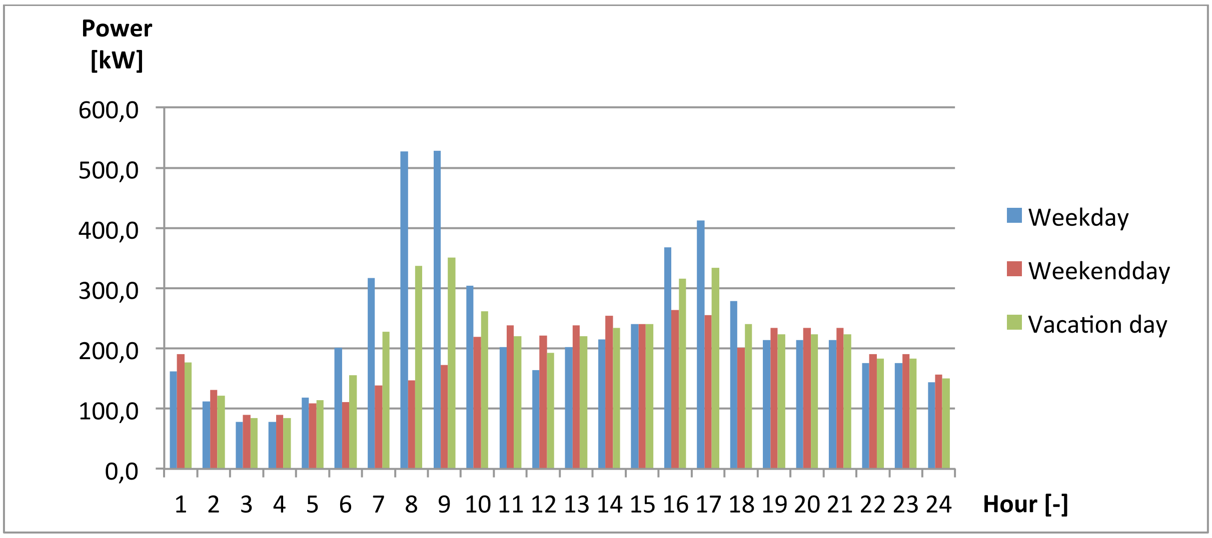

Figure 8: Average hourly power consumption in the PRT system simulated in Arena. The pod cars power consumption is estimated to be 1,5 times the pod cars at Heathrow.

The results seen in Figures 7 and 8 above was then put together into a whole year and the results are seen below in Table 3 and Figure 9.

Table 3: Scenario data

	Annual Electricity Consumption [MWh]	Rated power [kWp]	Annual Electricity Production [MWh]
Scenario (A)	1360	1670	1510
Scenario (B)	1910	2420	2070
Scenario (C)	1360	1040	930

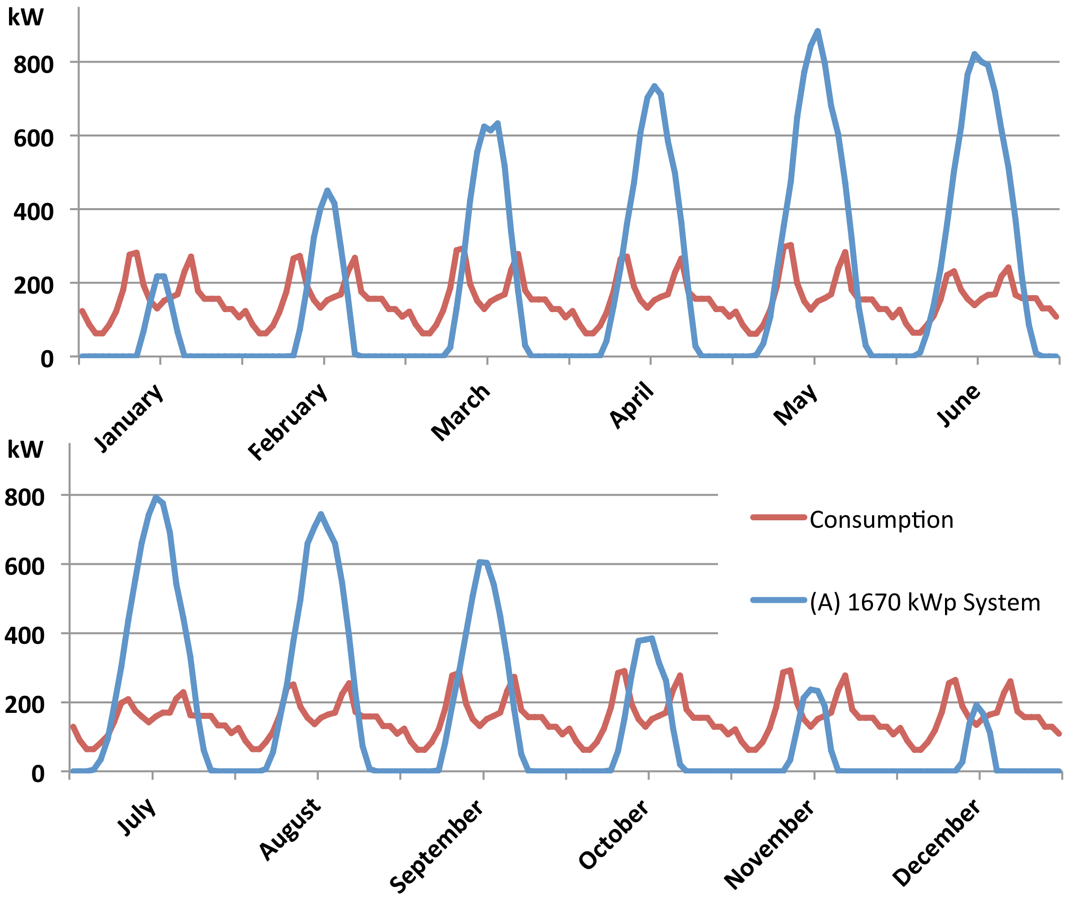

Figure 9: Electricity production and consumption for a typical day for each month during a whole year.

Energy Storage

Figure 10 below shows the impact on grid sales and buys from different sizes of energy storages. The figure shows that a smaller energy storage is sufficient to reduce consumption peaks and this kind of power storage is probably more interesting for PRT systems with a less developed grid. It is also possible to see that during March-September a relatively small storage (2 MWh) is more or less sufficient to achieve negligible electricity buys even with the simple controlling that was done in this case.

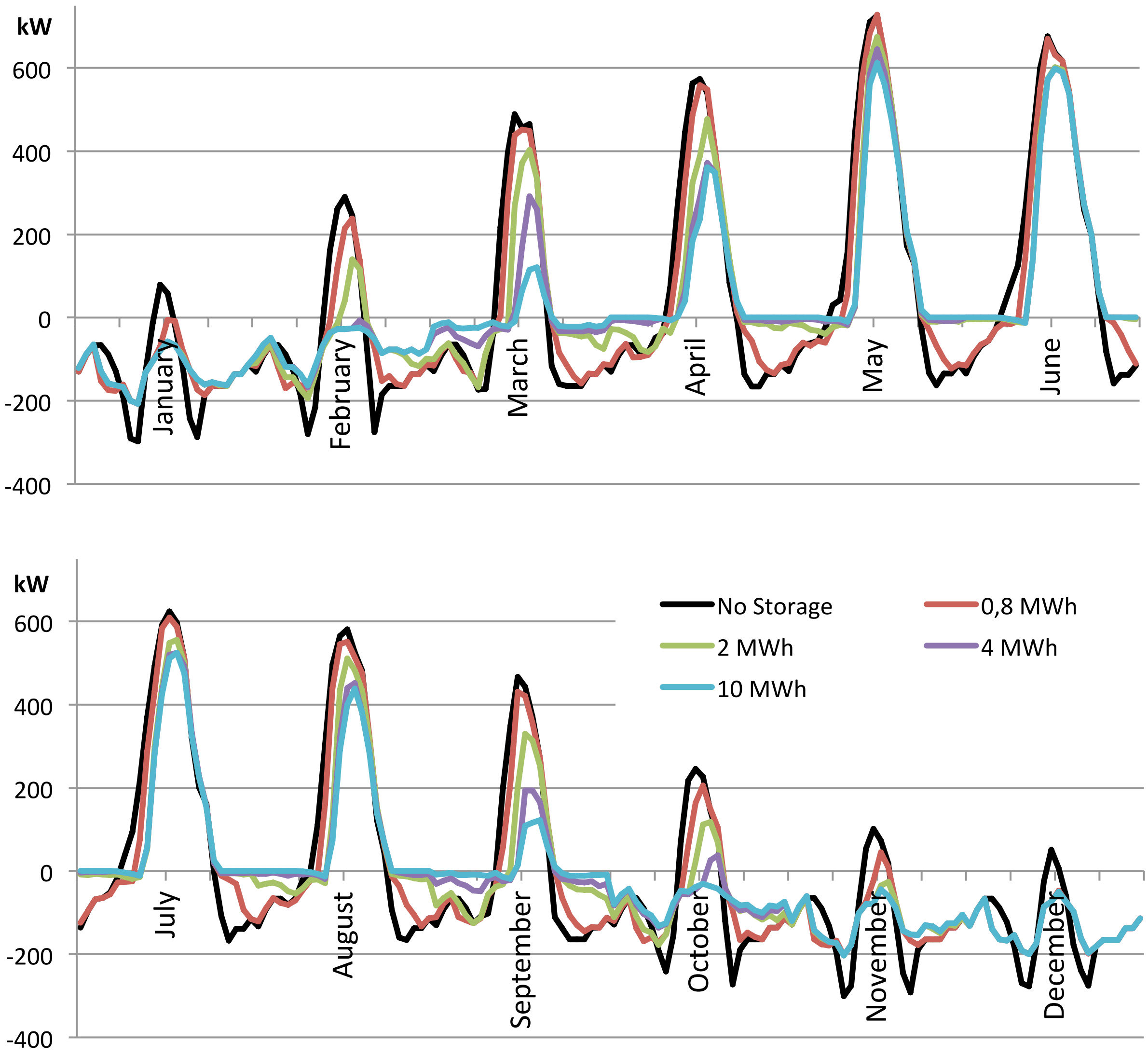

Figure 10: Grid deliveries for different sizes of energy storage during a typical day of teh month for a whole year. Positive values means sales, negative values means buys

Economic Calculations

Cost of PV

The standard module price of 16 SEK/W excl. VAT was used when calculating the costs for system installation. In this price, the costs for PV, module installation and required converters are included. Subsidies were subtracted from the costs with 1,2MSEK for each scenario, which is the maximum subsidy.

The costs for installing the three different scenarios are presented in table 4 on page 12. Scenario D was created as a complement to the already existing scenarios A, B and C. This additional scenario was used as a reference whereas no PV modules were installed and standard power consumption of 1,5 GWh per year was used. In this rough estimate, no internal rate was used, and it was assumed that electricity prices were constant. As an outcome of these assumptions, it is reasonable to believe that the applied internal rate will make the investment in PV modules seem less profitable. On the other hand, this factor may be countered as a result of the rising trend of integrating the Swedish grid system with the rest of Europe, raising Sweden's relatively low electricity prices. Further details are explained in sub-report X – 32 Electrical Grid Requirements. Table 4 shows prices and payback-time for PVs in the different scenarios.

Table 4: Cost of PVs for the three scenarios. The payback time has been calculated from the price difference between the specific scenario and the reference scenario, Scenario D.

Vattenfall	Scenario A	Scenario B	Scenario C	Scenario D
Annual electricity cost [kSEK]	215,5	316,8	496,5	1071,3
Investment cost [kSEK]	25520	37520	15440	0
Straight payback [yr]	25,7	31,6	22,6	-

Telge	Scenario A	Scenario B	Scenario C	Scenario D
Annual electricity cost [kSEK]	132,8	239,7	1016,1	2571,0
Investment cost [kSEK]	25520	37520	15440	0
Straight payback [yr]	10,5	11,1	9,9	-

Cost of Storage

The investment cost of different sized batteries for energy storage was roughly calculated using the results from a report by Divya & Østergaard (2009), presented in Table 5 and 6 below.

Table 5: Estimated prices for energy storages containing lead-acid batteries.

Lead-acid	Size of storage [MWh]				
Cost [kSEK]	0	0,8	2	4	10
Investment (low/high cost)	0	344 / 1031	859 / 2577	1718 / 5154	4295 / 12885
Annual, grid connection	225	187	182*	174*	152
Annual, Electricity (Vattenfall/Telge)	216 / 133	186 / 121	146 / 99	126 / 89	117 / 84
Straight Payback time (Low investment cost, Vattenfall/telge) [yr]	-	5 / 7	8 / 11	12 / 18	25 / 35
Straight Payback time (High investment cost, Vattenfall/telge) [yr]	-	15 / 21	23 / 33	37 / 54	75 / 106

*Linear extrapolation

Lifespan: 1000-2000 cycles, higher maintenance

Table 6: Estimated prices for energy storages containing li-ion batteries.

Li-ion	Size of storage [MWh]				
Cost [kSEK]	0	0,8	2	4	10
Investment (low/high cost)	0	4810 / 6872	12026 / 17180	24052 / 34360	60130 / 85900
Annual, grid connection	225	187	182*	174*	152
Annual, Electricity (Vattenfall/Telge)	216/133	186 /121	146 / 99	126 / 89	117 / 84
Straight Payback time (Low investment cost, Vattenfall/telge) [yr]	-	71 / 96	106 / 156	171 / 253	350 / 493
Straight Payback time (High investment cost, Vattenfall/telge) [yr]	-	101 / 137	152 / 223	244 / 362	499 / 704

*Linear extrapolation

Lifespan: 3000 cycles

In these rough estimations, the same assumptions as previously mentioned, regarding electricity prices contradicting internal rate, were made. It is predicted that the only economic benefits to be made, regarding battery storage, is lowering electricity and grid connection costs. There may however be other underlying factors that may result in making storage more feasible. For example, in Sweden, energy consumers pay for grid reinforcements, and there are rules regarding variation in energy load that affect the grid, a factor that may justify smaller battery storage.

As seen in the Table 5 and 6 above, the payback time for lead-acid batteries is shorter than for Li-ion batteries. The prices are estimated and the two different investment costs have been set to the highest and the lowest within the interval mentioned for the different battery types. These costs do not include maintenance and other system costs.

As discussed in sub-report X31 – Energy Storage, today's battery technology is rapidly improving; prices are dropping and new technologies being implemented. It is therefore inappropriate to decide which type of battery should be used, even just a few years from now. Presently, the best choice for battery storage is: Beginning with a lead-acid battery, and after the first lifetime, decide which technology to continue with in regard to new alternatives, since Li-ion batteries might be cheaper. There are also possibilities of installing minor electrical car batteries in each podcar, with too low energy density for cars that together, may act as relatively cheap large scale energy storage.

Discussion

PV modules on the PRT system are not a good investment for short-term payback. It may however be a reasonable investment considering all aspects. It would provide a unique selling point, since PV modules in close proximity to the PRT system, will help visualize possibilities of PV and other green energy. Track connected PVs will also help to promote the track, as opposed to more invisible installments on rooftops. This could simplify opportunities to receive funding's and promote Uppsala as an environmentally friendly city. Additionally, higher electricity prices and an increasing demand for renewable solar power could definitely raise the value of the investment. Uncertainties regarding future electricity prices make it difficult to predict how profitable it is to invest in PVs; to invest is also a way to protect the system from future possible higher costs. Table 4 on page 12 demonstrates that a smaller PV system, such as Scenario C as opposed to the larger Scenario A, is not significantly more profitable, even with Sweden's relatively low solar insolation.

Energy storage by batteries is today too expensive to be of use in Sweden. The electricity grid is strong enough to support a system of suggested size, but if a larger PV system is built, battery storage may become a more attractive solution in order to avoid expensive reinforcements of the grid. If electricity prices were to become higher and more fluctuating, battery storage could also become a better future investment. A system such as this, with PRT, PVs and energy storage, could be exported to developing countries or other locations with a less developed grid, and thereby, provide public transportation systems independent of fossil fuels. Additionally, most third world countries have better solar resources than Sweden, and therefore it would be possible to have a stand-alone PRT system, fully operational year around, if both PV and battery storage is utilized.

At the time this report was published, both PV module and large-scale battery storage are somewhat new technological sectors, developing rapidly. Uncertainties in future prices and potentials complicate calculations, but at the same point, these technologies may aid in creating better opportunities.

Matters to be Further Investigated

There are a number of areas to be further look into. The following list consists of suggested topics to further investigate regarding the subject.

- **Public Acceptance**
  In order to make PRT a natural choice for local transportation, opinion needs to be somewhat positive towards the building of the system. Investigating this is a matter that can be further looked into.
- **Construction Conditions**
  In order to decide the final design of the system, building permits need to be granted which may alter already set limits and change conditions. Additionally, installing PV-modules in conjunction with the renovation of a roof could cause problems with warranties, if there are any complications with the roof.
- **Other Types of PV-systems**
  To increase power production, one option is to install sun-tracking system for the PV-modules. A sun-tracking system would increase the efficiency but also raise the economic costs. It would be a good idea to investigate the cost efficiency for such a system.
- **Snow Loads**
  Matters on how the track will be affected by snow is another issue yet to be dealt with. This matter will most certainly not affect the rail, thanks to the roof and PV-modules above it, given that overhead protection is built along the entire track. Snow loads on the PV-modules, however, will affect the efficiency of the modules. The tilt on the PV-modules may also make snow to fall off the track, with risk for pedestrians and vehicles underneath.

- **Alternative System Design**
  To reduce system losses, 750 V DC could be drawn directly from the PV-strings. However, this would stray from the PV-module's MPP and probably cause more system losses than the solution with inverters followed by rectifiers.

Error Sources

- **Traveller statistics**
  Since the statistics are based on a limited amount of data collections, the accuracy of the results may be questionable. If statistics from UL had been provided, this uncertainty would have been reduced, increasing the precision of consumption-models.

- **Production simulations**
  Due to prerequisites given in the simulation program PVsyst, the actual system design may differ from the constructed models used. For example, solar panels with a maximum of two different tilt angles could be used for each simulation. Additionally, the models were constructed using measuring tools in Eniro, Google maps and real life approximations of object dimensions. Therefore, simulated shading losses may differ from actual losses.

- **Economic calculations**
  The economic calculations made in this report are based on today's prices. No concerns were taken regarding the variation of prices over time.

Conclusions

A PRT system, supported by PV modules without energy storage, is the most viable solution for a city such as Uppsala, given that a deal can be made with a company that sells solar produced electricity for a higher price than other electricity. If such a company could be allocated, it is possible to make a profit by overproducing electricity. There is little, or no economic incentive at all in building a PV system that only covers part of the PRT energy demand.

Regarding energy storage, if no requirements are set from the grid company regarding reinforcement and input/output to the grid, it is not economically advantageous to install a system for energy storage.

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SOLAR SKYWAYS

Report X11

[Travel Patterns Estimation]

Authors: Björn Isaksson, Erik Lindholm

2013-05-28

This report demonstrates how travel patterns for an ordinary weekday were estimated, what assumptions were made and which allocations were done in order to approximate the power consumption for the planned podcar system in Uppsala, Sweden. Results indicate that peak-travel hours occur between 7 – 9 am and 3 – 5 pm and therefore the PRT system experiences highest daily loads between these time periods.

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Method

Since the county councils transportation company (Upplands Lokaltrafik) does not have sufficiently detailed statistics, the first main goal of this study was to estimate the number of travellers for the planned system. This was accomplished by a simple traveller count on the bus services between the central station (Uppsala Central Station), the city hospital (Uppsala University Hospital), Uppsala Science Park and Uppsala Biomedical Centre (BMC). The amount of boarding and travelling passengers from the central station to the hospital, Science Park and BMC in the morning rush hour was counted, as well as the arriving passengers to the central station from the hospital and BMC in the afternoon rush hour. These two traveller flows may be assumed to be the two main flows of passengers during the day. Since the systems size and capacity will be determined from these two peaks it is critical that our estimate is as good as possible during these periods. Other times of the day was considered of less importance. Together with these counts, the number of employees and students, active along the different parts of the route was taken in mind. The aim of this study is to estimate the traveller flows during a typical day.

Assumptions

It is difficult to come up with a good estimation of the travelling flows in the planned system since the PRT system most certainly will change bus lines, car travels and travel habits. Therefore the simple assumption has been made to assume that the affected[1] bus services will be replaced by the PRT system at the planned route and its travellers will travel with the PRT according to our assumptions below. Additional travellers were also added, to account for people transferring from car travel to PRT commuting.

1. 70% of the people boarding a bus at the central station heading in the same direction as the PRT system will choose to travel by podcar instead. Additionally, 30% of the people already sitting in those buses will also use the PRT system since very few buses travel along a route similar to that of the PRT system. The remaining people using affected buses will choose a different route. People that travel further than within the limitations of the PRT system will change to different means of transportation at the end station (probably bus).
2. 70% of the people getting off an affected bus at the central station travelling from the direction of the PRT system will also use PRT instead of a bus and 30% of the remaining people on those buses will also choose PRT for the same reasons as in assumption 1.
3. An average of 9 000 trips will be done each day. This number is the average of earlier estimations of today's traffic and the traffic in a podcar system 2030. (Hunhammar, Lindström 2011, chapter 6).
4. More people will travel on weekdays than on weekends and weekend rush hours will occur later on average and be smoother. It is therefore assumed that approximately 10 000 trips will be made an average weekday and that 6 000 trips will be done an average weekend day.

[1] Affected implies the bus services that today operates the same route as the planned PRT-system (bus number: 3, 10, 12, 14, 40, 110, 111, and 115).

5. The curve describing travels to and from the central station will be relatively smooth, except on mornings from the central station, since commuters and in-city travellers will travel at the same time. These two groups will not coincide as much on other occasions.
6. The number of people travelling in either direction 6-10 o'clock will be roughly the same as the number of people travelling in the other direction 14-22 o'clock.
7. The travels in the two directions of the system are estimated to be equal, i.e. 50% each. Travels between the three inner city stations and the hospital, and travels between the three inner city stations and BMC are assumed to make up for 30%, respectively 40% of the daily travels. The remaining 30% are assumed to be travels between the city and Uppsala Science Park, internal travel at the hospital and shorter random travels between nearby stations.

These few assumptions will not generate a complete estimation of the travel flows once the PRT system is in operation. They will, however, give us a place to start when trying to form a rough estimate of when and how many people are travelling on the planned route.

Collected Data

Data collected when counting boardings, get offs and travels at Uppsala central station is shown below in Figures 1-4.

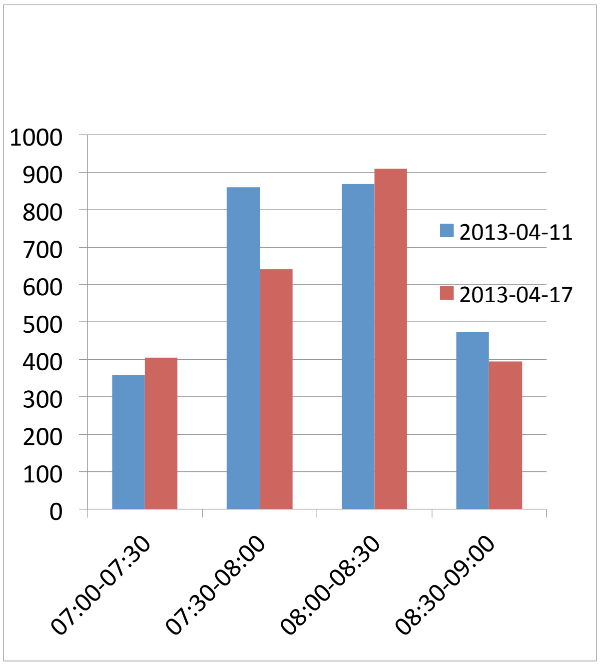


Figure 1: Passengers traveling with the bus services from Uppsala central station to the destinations on the planned PRT route in the morning rush hours.

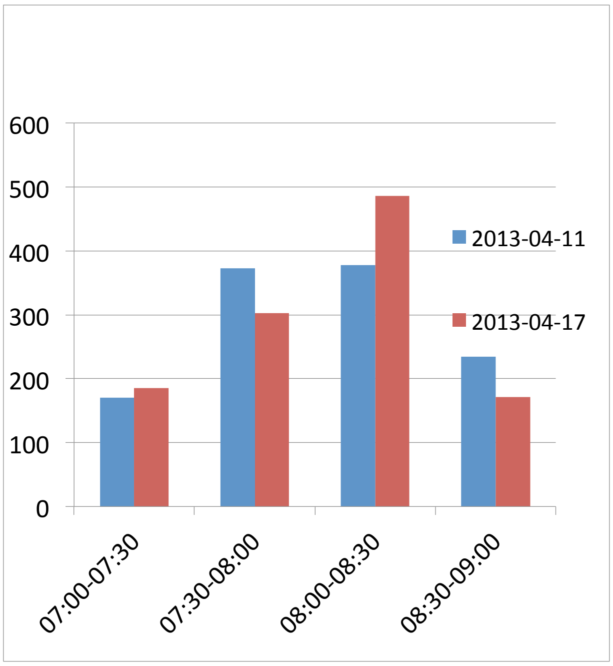
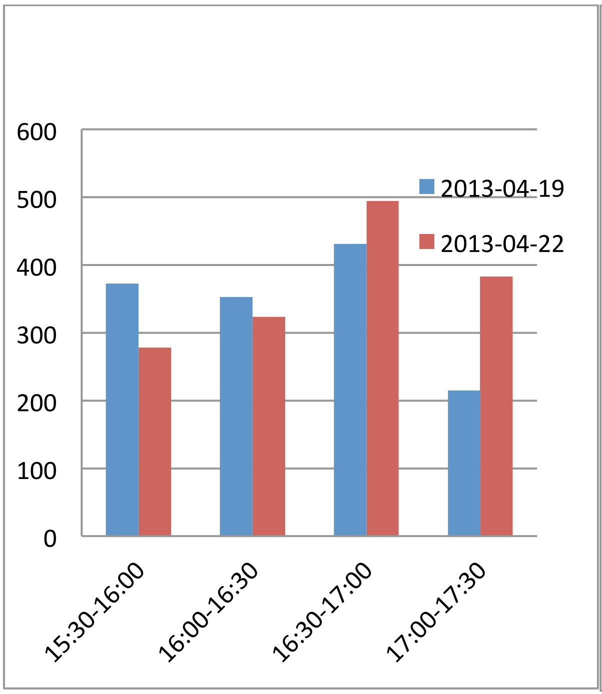


Figure 2: Passengers boarding the bus services at the Uppsala central station to the destinations on the planned PRT route in the morning rush hours.



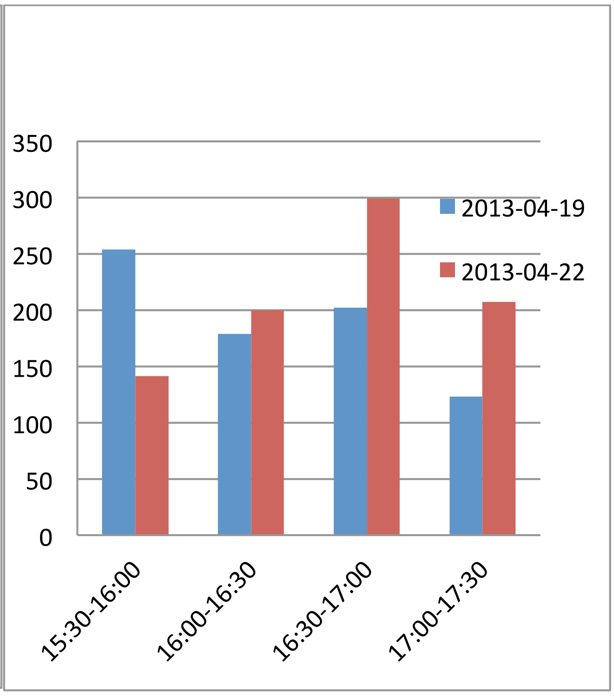


Figure 3: Passengers arriving to the Uppsala central station from the stations on the planned PRT route in the afternoon rush hours.

Figure 4: Passengers disembarking at the Uppsala central station from the stations on the planned PRT route in the afternoon rush hours.

Only two measurements were done in the morning respectively in the afternoon. If the goal was to investigate peoples travel patterns on the route today, this would not provide statistically reliable figures. Two measurements can however be enough if the goal is to estimate a reasonable time of day and number of people that will travel in the podcar system years from now. It is reasonable that all the assumptions that are done in order to be able to estimate travel patterns affects the result more than any statistical uncertainty due to lack of measurements.

Allocations

In order to model all the travels during a day, assumptions were made of how to distribute the traveller's origins and destinations in the system. Of the assumed 10 000 travellers during a weekday, 50%, i.e. 5 000 are assumed to travel in each direction.

It was assumed that 15% of the employees and the daily visitors to Uppsala University Hospital would travel two ways with the planned PRT system. This would make up to 3 000 trips per day (Uppsala University Hospital 2012). In the same way, assumptions that 25 % of the employees in Uppsala Science Park and 15% of the employees and students at BMC will travel with the system were made, yielding in 3 000 additional trips per day. (Hunhammar, Lindström 2011). The last 4 000 trips are mainly distributed between the inner city stations and BMC, but also as internal travels around the hospital and as shorter random travel between nearby stations. Table 1 shows which assumptions were made when estimating traveller allocations. Tables 2-25 show the detailed distribution of travellers that were used in later Arena-simulations.

Table 1: The main travel assumptions in the system. Underlined numbers are estimated travels by employees, visitors and students to UUH, Science Park or BMC. Black numbers are travellers, traveling to or from other locations.

	Trips	Percentage %
Southbound	**5000**	
Scattered trips and UUH internal	750	15
City-UUH	1500	30
City-Science Park	750	15
City-BMC	(750+1250)=2000	40
Northbound	**5000**	
BMC-City	(750+1250)=2000	40
Science Park-City	750	15
UUH-City	1500	30
Scattered trips & UUH internal	750	15

Results

Figures seven and eight in appendix one shows estimated travel patterns for a weekday from and to Uppsala central station. For the assumptions made in order to make the estimated values, see the heading "assumptions".

Figures five and six below shows estimated travel patterns for southbound and northbound travellers, the difference between these and Figures seven and eight is that approximately 1 000 travellers were added in each direction according to earlier assumptions, i.e. car travellers changing to PRT travels etc. These two graphs are assumed to be the travel patterns for the whole system a regular weekday. The assumed travel peaks at 7-9 am and 15-17 have been confirmed by Anders Bergqvist at UL (2013).

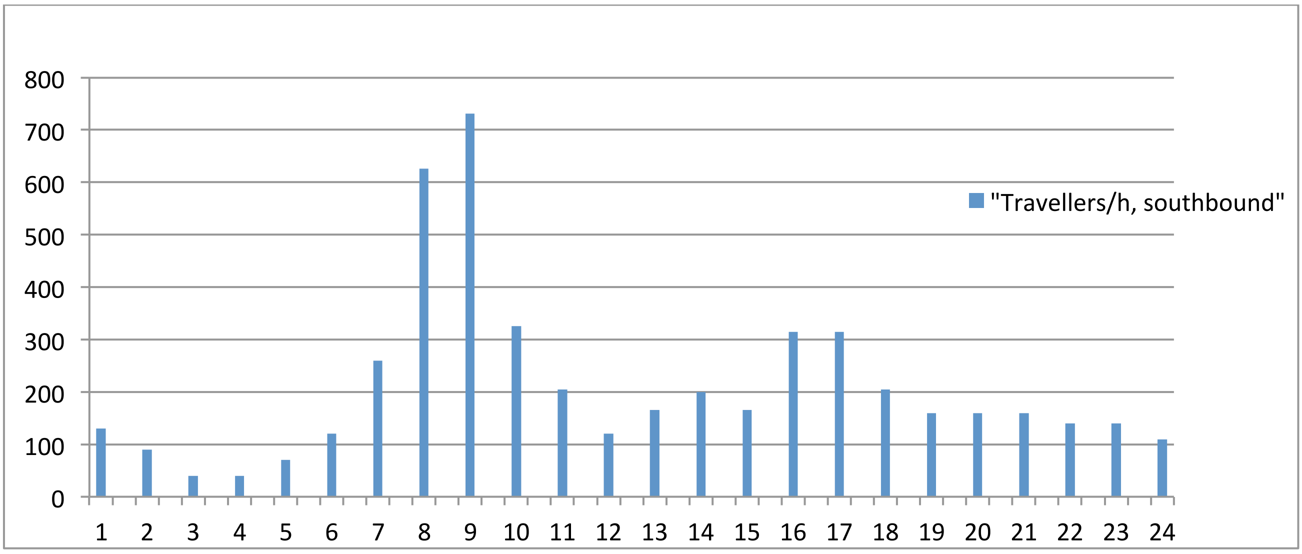


Figure 5: Estimated travel patterns for southbound travellers per hour.

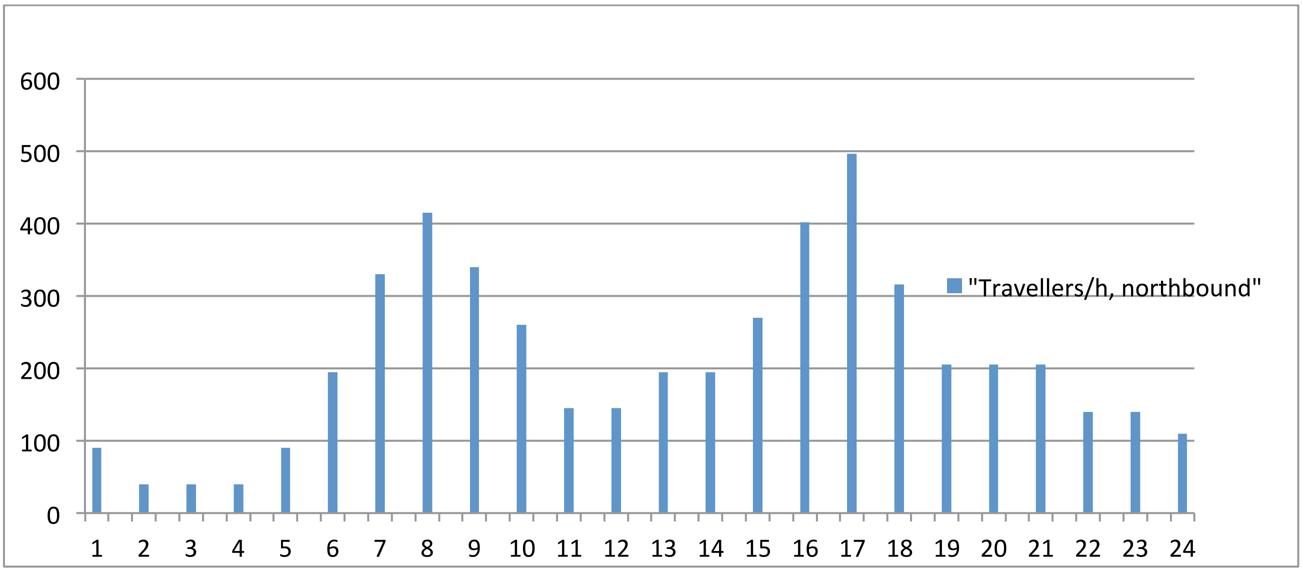


Figure 6: Estimated travel patterns for northbound travellers per hour.

Comments on Results

These results are only the results for a typical weekday. For a full year result, se report X22 – Travel simulations in Arena. The assumptions that were made from today's travel behaviour create two distinct peaks per day. When a PRT system is implemented, it is possible that travel habits may change, due to the convenience of travel. This could change behaviours, for example more mid-day travel.

References

Hunhammar, M. Lindström, C. (2011) *Introduction of PRT in Uppsala - IST report 2011:1* Uppsala

Uppsala University Hospital (2012), *Kort Fakta*
http://www.akademiska.se/sv/Om-Akademiska/Korta-fakta/
Read 2013-04-25

Bergqvist, A., analyst at UL, *Conversation re. travel patterns in Uppsala city,* 2013-05-24

Appendix 1 – Additional Tables and Figures

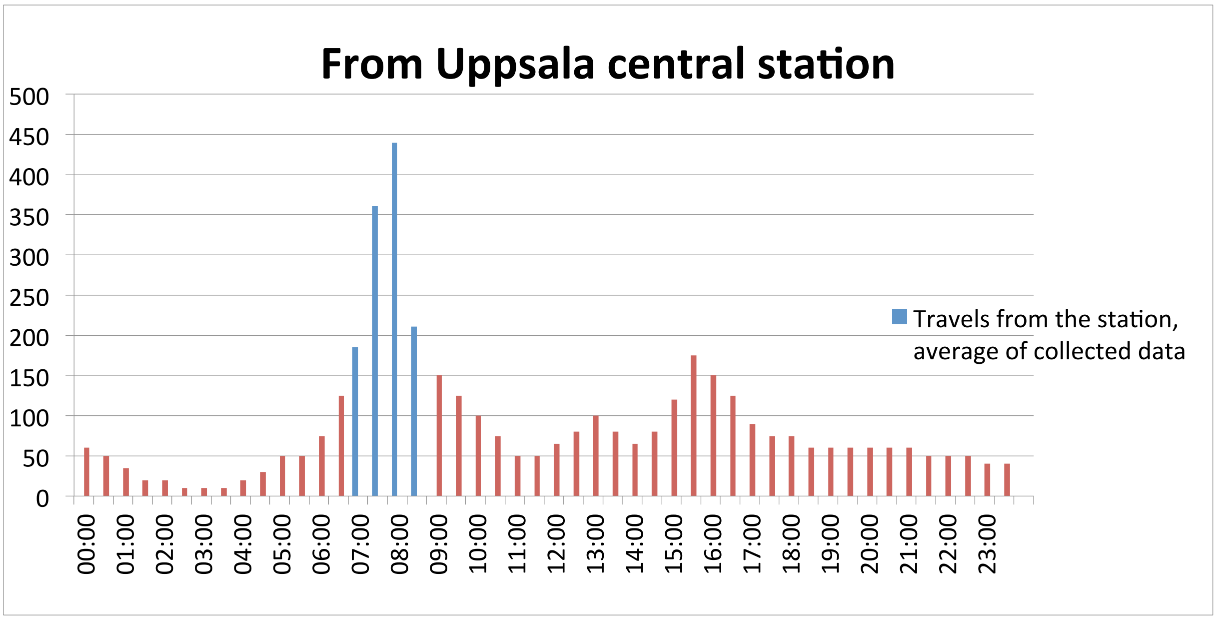


Figure 7

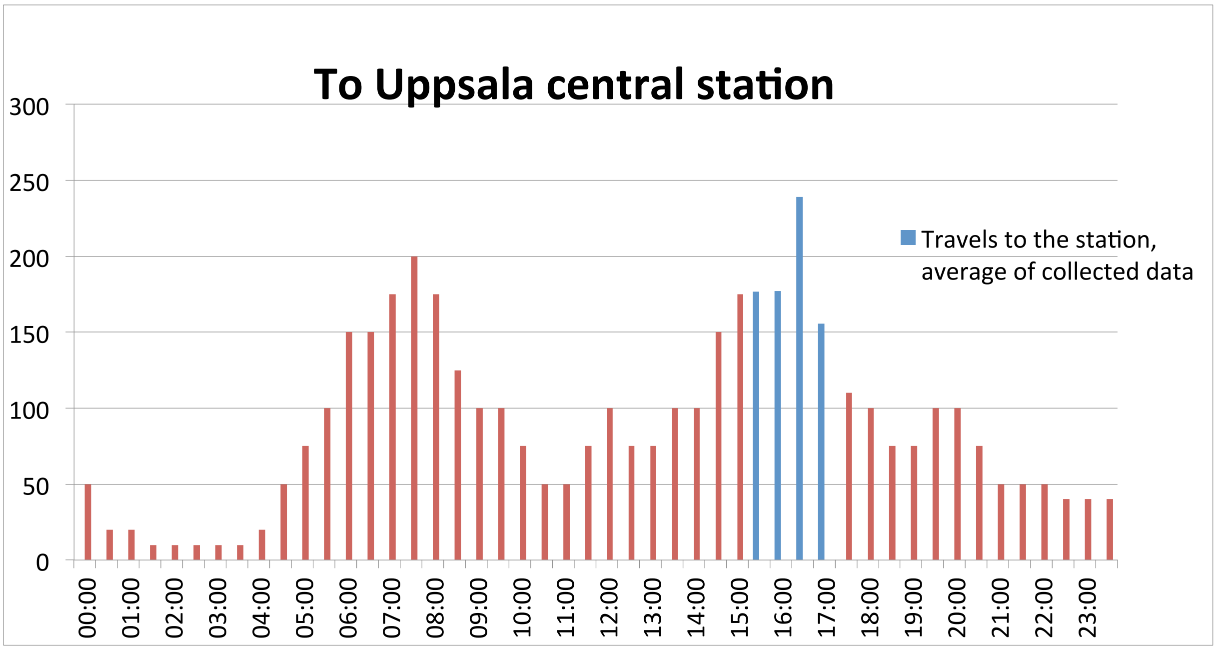


Figure 8

Table 2

00:00-01:00 — From station

To station	1	2	3	4	5	6	7	8	9	10	Total to		
1	x	0	1	2,5	5	5	5	2,75	2,75	10	34		
2	1	x	0	0	3	2	2	1	1	6	16		
3	2	0	x	1	3	2	2	1	1	6	18		
4	4,5	2	0	x	1	1	1	0	0	3	12,5		
5	5,4	4	4	2	x	2	1	0	0	3	21,4	h=1	Travelling (N/S
6	5,3	4	4	2	1	x	1	1	1	3	22,3		90/130
7	5,3	4	4	2	1	1	x	1	1	3	22,3		
8	2,75	2	2	1	1	1	0	x	0	1	10,75		
9	2,75	2	2	1	1	1	0	0	x	1	10,75		
10	22	8	8	3	3	3	3	1	1	x	52		
Total from	51	26	25	14,5	19	18	15	7,75	7,75	36	**Total:** 220	220	

Table 3

01:00-02:00 — From station

To station	1	2	3	4	5	6	7	8	9	10	Total to		
1	x	0	1	1	1,4	2,3	2,3	1	1	6	16		
2	0	x	0	1	1	1	1	0	0	4	8		
3	1	0	x	0	1	1	1	1	1	2	8		
4	2,5	1	0	x	1	1	0	0	0	2	7,5		
5	5	3	3	1	x	0	1	0	0	0	13	h=2	Travelling (N/S)
6	5	2	2	1	2	x	0	0	0	1	13		40/90
7	5	2	2	1	1	1	x	1	1	1	15		
8	2,75	1	1	0	0	1	1	x	0	0	6,75		
9	2,75	1	1	0	0	1	1	0	x	0	6,75		
10	10	6	6	3	3	3	3	1	1	x	36		
Total from	34	16	16	8	10,4	11,3	10,3	4	4	16	**Total:** 130	130	

Table 4

02:00-03:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	0	1	1	1,4	2,3	2,3	1	1	6	16		
	2	0	x	0	1	1	1	1	0	0	4	8		
	3	1	0	x	0	1	1	1	1	1	2	8		
	4	1	1	0	x	1	1	0	0	0	2	6		
To station	5	1,4	1	1	1	x	0	1	0	0	0	5,4	h=3	Travelling (N/S)
	6	2,3	1	1	1	0	x	0	0	0	1	6,3		40/40
	7	2,3	1	1	0	1	0	x	1	1	1	8,3		
	8	1	0	1	0	0	0	1	x	0	0	3		
	9	1	0	1	0	0	0	1	0	x	0	3		
	10	6	4	2	2	0	1	1	0	0	x	16		
	Total from	16	8	8	6	5,4	6,3	8,3	3	3	16	**Total:** 80	80	

Table 5

03:00-04:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	0	1	1	1,4	2,3	2,3	1	1	6	16		
	2	0	x	0	1	1	1	1	0	0	4	8		
	3	1	0	x	0	1	1	1	1	1	2	8		
	4	1	1	0	x	1	1	0	0	0	2	6		
To station	5	1,4	1	1	1	x	0	1	0	0	0	5,4	h=4	Travelling (N/S)
	6	2,3	1	1	1	0	x	0	0	0	1	6,3		40/40
	7	2,3	1	1	0	1	0	x	1	1	1	8,3		
	8	1	0	1	0	0	0	1	x	0	0	3		
	9	1	0	1	0	0	0	1	0	x	0	3		
	10	6	4	2	2	0	1	1	0	0	x	16		
	Total from	16	8	8	6	5,4	6,3	8,3	3	3	16	**Total:** 80		

Table 6

04:00-05:00 — From station

		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	0	1	2,5	5	5	5	2,75	2,75	10	34		
	2	0	x	0	0	3	2	2	1	1	6	15		
	3	1	0	x	1	3	2	2	1	1	6	17		
	4	3,5	0	0	x	1	1	1	0	0	3	9,5		
To station	5	3,4	3	2	1	x	2	1	0	0	3	15,4	h=5	Travelling (N/S)
	6	3,3	2	2	1	0	x	1	1	1	3	14,3		90/70
	7	3,3	2	2	0	1	1	x	1	1	3	14,3		
	8	1,25	1	1	1	0	0	1	x	0	1	6,25		
	9	1,25	1	1	1	0	0	1	0	x	1	6,25		
	10	10	6	5	2	1	2	2	0	0	x	28		
Total from		27	15	14	9,5	14	15	16	6,75	6,75	36	**Total:** 160		

Table 7

05:00-06:00 — From station

		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	2	4,75	8	7	7	4,75	4,5	35	74		
	2	1	x	0	3	6	6	6	2	2	15	41		
	3	2	0	x	4	6	5	5	3	3	11	39		
	4	2	1	1	x	3	3	3	1	1	3	18		
To station	5	5	5	3	2	x	3	3	1	1	4	27	h=6	Travelling (N/S)
	6	6	4	3	2	1	x	2	2	2	3	25		195/120
	7	5	4	3	1	2	1	x	1	1	5	23		
	8	2	1	2	1	1	1	1	x	0	1	10		
	9	2	1	2	1	1	1	1	0	x	1	10		
	10	12	9	8	6	2	4	4	2	1	x	48		
Total from		37	26	24	24,8	30	31	32	16,8	15,5	78	**Total:** 315		

Table 8

06:00-07:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	2	10,5	17	17	17	6,75	6,75	33	111		
	2	1	x	1	4	13	13	13	5	5	18	73		
	3	3	1	x	2	6	6	6	3	3	14	44		
	4	10	5	2	x	4	3	3	1	1	9	38		
To station	5	11,6	8	5	4	x	4	3	2	2	8	47,6	h=7	Travelling (N/S)
	6	11,7	8	5	2	5	x	4	3	3	14	55,7		330/260
	7	11,7	8	5	2	5	3	x	3	3	14	54,7		
	8	5,5	3	3	1	2	3	2	x	1	12	32,5		
	9	5,5	3	3	1	2	2	2	1	x	10	29,5		
	10	27	16	12	6	10	12	12	5	4	x	104		
	Total from	87	53	38	32,5	64	63	62	29,8	28,8	132	**Total:** 590		

Table 9

07:00-08:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	3	13	19	19	19	9	8	44	135		
	2	1	x	1	6	14	14	13	6	6	32	93		
	3	25	6	x	3	9	9	9	4	4	20	89		
	4	13	10	4	x	6	6	6	3	3	11	62		
To station	5	27	17	15	8	x	6	6	3	3	15	100	h=8	Travelling (N/S)
	6	27	17	15	8	8	x	5	3	3	15	101		415/625
	7	27	17	15	6	8	8	x	3	3	16	103		
	8	13	10	7	4	4	4	4	x	1	8	55		
	9	13	10	7	4	4	4	4	1	x	5	52		
	10	80	55	25	10	20	20	20	10	10	x	250		
	Total from	226	143	92	62	92	90	86	42	41	166	**Total:** 1040		

Table 10

08:00-09:00		From station											
		1	2	3	4	5	6	7	8	9	10	Total to	
	1	x	1	3	8	16	15	14	6	6	34	103	
	2	1	x	1	6	12	10	10	4	4	20	68	
	3	8	1	x	3	9	8	7	4	4	15	59	
	4	17	11	5	x	6	4	4	2	2	8	59	
To station	5	45	25	15	7	x	6	5	3	3	14	123	h=9 Travelling (N/S)
	6	45	25	15	7	5	x	5	3	3	15	123	340/731
	7	40	25	15	7	5	5	x	3	3	14	117	
	8	20	8	5	5	6	5	6	x	1	9	65	
	9	14	10	8	5	6	5	6	1	x	7	62	
	10	87	65	45	10	20	20	20	15	10	x	292	
	Total from	277	171	112	58	85	78	77	41	36	136	**Total:** 1071	

Table 11

09:00-10:00		From station											
		1	2	3	4	5	6	7	8	9	10	Total to	
	1	x	1	4	4	10	10	10	5	5	34	83	
	2	1	x	1	4	8	8	7	4	4	20	57	
	3	2	1	x	1	5	5	5	3	3	15	40	
	4	10	3	2	x	4	4	4	1	1	2	31	
To station	5	18	11	6	2	x	4	4	2	2	10	59	h=10 Travelling (N/S)
	6	18	11	6	6	3	x	4	2	2	10	62	260/325
	7	18	10	6	6	3	3	x	2	2	10	60	
	8	8	6	3	1	2	2	2	x	1	2	27	
	9	8	6	3	1	2	2	2	1	x	1	26	
	10	40	30	20	10	10	10	10	5	5	x	140	
	Total from	123	79	51	35	47	48	48	25	25	104	**Total:** 585	

Table 12

10:00-11:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	2	3	7	7	7	4	4	19	54		
	2	1	x	1	2	5	5	5	2	2	12	35		
	3	2	1	x	1	3	3	3	2	2	8	25		
	4	4	3	1	x	2	2	2	1	1	4	20		
To station	5	10	7	7	3	x	2	2	0	0	4	35	h=11	Travelling (N/S)
	6	10	7	4	3	3	x	1	1	1	4	34		145/205
	7	9	7	4	2	3	3	x	0	1	4	33		
	8	5	3	2	1	1	1	1	x	0	2	16		
	9	5	3	2	1	1	1	1	1	x	1	16		
	10	30	17	10	5	5	5	5	3	2	x	82		
	Total from	76	49	33	21	30	29	27	14	13	58	**Total:** 350		

Table 13

11:00-12:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	2	3	7	7	7	4	4	19	54		
	2	1	x	1	2	5	5	5	2	2	12	35		
	3	1	1	x	1	3	3	3	2	2	8	24		
	4	1	1	1	x	2	2	2	1	1	4	15		
To station	5	7	4	2	1	x	2	2	0	0	4	22	h=12	Travelling (N/S
	6	7	4	2	1	2	x	1	1	1	4	23		145/120
	7	7	4	2	1	2	2	x	0	1	4	23		
	8	3	2	1	0	1	1	1	x	0	2	11		
	9	3	2	1	0	1	1	1	0	x	1	10		
	10	16	12	8	1	3	3	3	1	1	x	48		
	Total from	46	31	20	10	26	26	25	11	12	58	**Total:** 265		

Table 14

12:00-13:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	2	4,75	8	7	7	4,75	4,5	35	74		
	2	2	x	0	3	6	6	6	2	2	15	42		
	3	2	2	x	4	6	5	5	3	3	11	41		
	4	5	3	1	x	3	3	3	1	1	3	23		
To station	5	8	5	3	2	x	3	3	1	1	4	30	h=13	Travelling (N/S)
	6	8	5	3	2	2	x	2	2	2	3	29		195/165
	7	8	5	3	2	2	2	x	1	1	5	29		
	8	4	2	2	1	1	1	1	x	0	1	13		
	9	4	2	2	1	1	1	1	0	x	1	13		
	10	20	15	10	6	4	4	4	2	1	x	66		
	Total from	61	40	26	25,8	33	32	32	16,8	15,5	78	**Total:** 360		

Table 15

13:00-14:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	2	4,75	8	7	7	4,75	4,5	35	74		
	2	1	x	0	3	6	6	6	2	2	15	41		
	3	2	1	x	4	6	5	5	3	3	11	40		
	4	4	3	1	x	3	3	3	1	1	3	22		
To station	5	10	6	6	3	x	3	3	1	1	4	37	h=14	Travelling (N/S)
	6	10	6	4	3	3	x	2	2	2	3	35		195/200
	7	9	6	4	2	3	3	x	1	1	5	34		
	8	5	3	2	1	1	1	1	x	0	1	15		
	9	5	3	2	1	1	1	1	1	x	1	16		
	10	30	16	10	5	5	5	5	3	2	x	81		
	Total from	76	45	31	26,8	36	34	33	18,8	16,5	78	**Total:** 395		

Table 16

14:00-15:00	From station												
		1	2	3	4	5	6	7	8	9	10	Total to	
	1	x	1	5	5	10	10	10	6	6	35	88	
	2	2	x	1	4	8	8	8	4	4	20	59	
	3	2	2	x	1	8	8	8	7	4	4	44	
	4	5	3	1	x	1	5	5	5	3	3	31	
To station	5	8	5	3	2	x	4	4	3	3	10	42	h=15 Travelling (N/S)
	6	8	5	3	2	2	x	4	3	3	10	40	270/165
	7	8	5	3	2	2	2	x	2	3	10	37	
	8	4	2	2	1	1	1	1	x	1	2	15	
	9	4	2	2	1	1	1	1	0	x	1	13	
	10	20	15	10	6	4	4	4	2	1	x	66	
	Total from	61	40	30	24	37	43	45	32	28	95	**Total:** 435	

Table 17

15:00-16:00	From station												
		1	2	3	4	5	6	7	8	9	10	Total to	
	1	x	1	3	13	18	18	18	9	8	44	132	
	2	1	x	1	6	13	13	13	6	6	32	91	
	3	2	1	x	3	9	9	9	4	4	20	61	
	4	10	3	2	x	6	6	6	3	3	11	50	
To station	5	16	10	6	2	x	5	5	3	3	13	63	h=16 Travelling (N/S)
	6	16	10	6	6	2	x	4	3	3	13	63	402/315
	7	16	10	6	6	3	3	x	3	3	13	63	
	8	8	6	3	1	2	2	2	x	1	9	34	
	9	8	6	3	1	2	2	2	1	x	6	31	
	10	40	30	20	5	8	8	8	5	5	x	129	
	Total from	117	77	50	43	63	66	67	37	36	161	**Total:** 717	

Table 18

16:00-17:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	3	15	20	20	20	15	15	60	169		
	2	1	x	1	8	15	15	15	8	8	45	116		
	3	2	1	x	3	9	9	9	4	4	30	71		
	4	10	3	2	x	6	6	6	3	3	12	51		
To station	5	16	10	6	2	x	6	6	6	6	13	71	h=17	Travelling (N/S)
	6	16	10	6	6	2	x	6	6	6	13	71		496/315
	7	16	10	6	6	3	3	x	6	6	13	69		
	8	8	6	3	1	2	2	2	x	1	9	34		
	9	8	6	3	1	2	2	2	1	x	5	30		
	10	40	30	20	5	8	8	8	5	5	x	129		
	Total from	117	77	50	47	67	71	74	54	54	200	**Total:** 811		

Table 19

17:00-18:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	2	10,5	17	17	17	6,75	6,75	30	108		
	2	1	x	1	4	13	13	13	5	5	18	73		
	3	2	1	x	2	6	6	6	3	3	14	43		
	4	4	3	1	x	4	3	3	1	1	9	29		
To station	5	10	7	7	3	x	4	3	2	2	8	46	h=18	Travelling (N/S)
	6	10	7	4	3	3	x	3	3	3	12	48		316/205
	7	9	7	4	2	3	3	x	3	3	12	46		
	8	5	3	2	1	1	1	1	x	1	8	23		
	9	5	3	2	1	1	1	1	1	x	8	23		
	10	30	17	10	5	5	5	5	3	2	x	82		
	Total from	76	49	33	31,5	53	53	52	27,8	26,8	119	**Total:** 521		

Table 20

18:00-19:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	2	5	8	7	7	5	5	35	75		
	2	2	x	1	3	6	6	6	2	2	15	43		
	3	2	2	x	4	6	5	5	3	3	11	41		
	4	4	2	1	x	3	3	3	1	1	4	22		
To station	5	8	5	3	2	x	3	3	2	2	4	32	h=19	Travelling (N/S)
	6	8	5	3	2	2	x	3	2	2	4	31		205/160
	7	8	5	3	2	2	2	x	2	2	5	31		
	8	4	2	2	1	1	1	1	x	1	1	14		
	9	4	2	2	1	1	1	1	0	x	1	13		
	10	20	15	10	6	3	3	3	2	1	x	63		
Total from		60	39	27	26	32	31	32	19	19	80	**Total:** 365		

Table 21

19:00-20:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	2	5	8	7	7	5	5	35	75		
	2	2	x	1	3	6	6	6	2	2	15	43		
	3	2	2	x	4	6	5	5	3	3	11	41		
	4	4	2	1	x	3	3	3	1	1	4	22		
To station	5	8	5	3	2	x	3	3	2	2	4	32		Travelling (N/S)
	6	8	5	3	2	2	x	3	2	2	4	31	h=20	205/160
	7	8	5	3	2	2	2	x	2	2	5	31		
	8	4	2	2	1	1	1	1	x	1	1	14		
	9	4	2	2	1	1	1	1	0	x	1	13		
	10	20	15	10	6	3	3	3	2	1	x	63		
Total from		60	39	27	26	32	31	32	19	19	80	**Total:** 365		

Table 22

20:00-21:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	2	5	8	7	7	5	5	35	75		
	2	2	x	1	3	6	6	6	2	2	15	43		
	3	2	2	x	4	6	5	5	3	3	11	41		
	4	4	2	1	x	3	3	3	1	1	4	22		
To station	5	8	5	3	2	x	3	3	2	2	4	32		Travelling (N/S)
	6	8	5	3	2	2	x	3	2	2	4	31	h=21	205/160
	7	8	5	3	2	2	2	x	2	2	5	31		
	8	4	2	2	1	1	1	1	x	1	1	14		
	9	4	2	2	1	1	1	1	0	x	1	13		
	10	20	15	10	6	3	3	3	2	1	x	63		
	Total from	60	39	27	26	32	31	32	19	19	80	**Total:** 365		

Table 23

21:00-22:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	2	3	6	6	6	4	4	17	49		
	2	1	x	1	2	5	5	5	2	2	12	35		
	3	2	1	x	1	3	3	3	2	2	8	25		
	4	5	2	1	x	2	2	2	1	1	4	20		
To station	5	6	4	4	2	x	2	2	0	0	4	24		Travelling (N/S)
	6	6	4	4	2	2	x	1	1	1	4	25	h=22	140/140
	7	6	4	4	2	2	1	x	0	1	4	24		
	8	3	2	2	1	1	1	1	x	0	2	13		
	9	3	2	2	1	1	1	1	1	x	1	13		
	10	22	8	8	3	3	3	3	1	1	x	52		
	Total from	54	28	28	17	25	24	24	12	12	56	**Total:** 280		

Table 24

22:00-23:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	2	3	6	6	6	4	4	17	49		
	2	1	x	1	2	5	5	5	2	2	12	35		
	3	2	1	x	1	3	3	3	2	2	8	25		
	4	5	2	1	x	2	2	2	1	1	4	20		
To station	5	6	4	4	2	x	2	2	0	0	4	24		Travelling (N/S)
	6	6	4	4	2	2	x	1	1	1	4	25	h=23	140/140
	7	6	4	4	2	2	1	x	0	1	4	24		
	8	3	2	2	1	1	1	1	x	0	2	13		
	9	3	2	2	1	1	1	1	1	x	1	13		
	10	22	8	8	3	3	3	3	1	1	x	52		
	Total from	54	28	28	17	25	24	24	12	12	56	**Total:** 280		

Table 25

23:00-24:00		From station												
		1	2	3	4	5	6	7	8	9	10	Total to		
	1	x	1	1	3	6	6	6	4	4	10	41		
	2	1	x	1	1	3	2	2	1	1	6	18		
	3	2	0	x	1	3	2	2	1	1	6	18		
	4	2	1	1	x	1	1	1	1	1	3	12		
To station	5	5	5	3	2	x	2	1	2	2	3	25		Travelling (N/S)
	6	5	4	3	2	1	x	1	2	2	3	23	h=24	110/110
	7	5	4	3	1	2	1	x	2	2	3	23		
	8	2	1	2	1	1	1	1	x	1	1	11		
	9	2	1	2	1	1	1	1	1	x	1	11		
	10	10	8	6	6	2	2	2	1	1	x	38		
	Total from	34	25	22	18	20	18	17	15	15	36	**Total:** 220		

Report X12

[Placement of Modules]

Author: Joakim Björk

2013-05-28

In order to optimize electricity production, a wide range of simulations, with a fixed axis and different combinations of placements and orientations of the PV modules, were executed and analyzed. Results indicate that it is ideal, in terms of energy production, to have PV modules facing south and that optimizing the azimuth is of greater importance than the tilt angle. However, since the route of the PRT system already is definite, it is not possible to change the azimuth orientation.

Report X12
Joakim Björk
2013-05-28

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Background

The optimal placement of fixed PV modules is 0° azimuth, or directly south, in the northern hemisphere. This will allow the modules to capture the most of the sunlight during the day, and thereby producing the maximum amount of energy. The problem is that this will give the peak production at noon, while the PRT system will have its top consumption at roughly 8 a.m. and 4 p.m. The same problem goes for PV installments in private houses. This problem can be solved either by selling the electricity to the grid when produced at noon and buying when consumption is at its top, or using electrical storage like batteries. Another way to match the consumption need is to face the PV modules in different azimuths. Doing this will lower the overall energy production, but it might be possible to better fit the power demand, since this will shift the peak production point of the day.

The tilt of the module relative to the horizon is also an important parameter when it comes to PV module efficiency. Naturally the optimal placement of the module would be to always face the sun perpendicularly. This, on the other hand, requires an installation of panels with two moveable axes, and the benefit contra cost and upkeep of moveable parts is not always beneficial. For a fixed panel facing 0° azimuth in Uppsala, with latitude of 60°, the optimal tilt is 45°. This placement will optimize the overall yearly production. The optimum tilt will however vary with the seasons. During summer when the sun reaches higher the optimal tilt lies around 35°, while being around 70° during winter when the sun reaches lower in the sky, according to simulations in the simulation software PVsyst. The albedo of the ground also affects the optimal placement, favoring a higher tilt, especially during the winter when the ground is covered in snow. In cloudy areas or highly polluted locations, when the modules rarely face direct sunlight, it could be beneficial to place the modules with a lower tilt. This will allow the panels to see a larger portion of the sky, thereby beneficing more from diffuse radiation (Labouret, A., Villoz, M. 2010).

For the PV installments in the PRT system the azimuth of the modules will be set by the directions of the tracks, with exception of modules placed on the station rooftops and other areas. For esthetic reasons, whereas the track will run through the city, the modules will not be placed as a 7 meter wide PV array running along the track in a 45° tilt, but rather be broken with two or more different angles. For simplicity, a design with two PV arrays connected to form a roof over the track with approximately 30° resp. 60° tilt will be investigated. This report will describe the yearly and daily production curves for different azimuths and tilts. Also the difference of using two PV arrays with non-optimal tilt supposed to a larger PV array with optimum tilt.

It is possible to use a seasonal or daily tracking system for the panels. A vertical tracking system is the most efficient form of tracking in high latitudes such as Uppsala's. The possibility for sun-tracking along the PRT track would be by a horizontal axis. This is more beneficial for lower latitudes and might help in dealing with glare and overheating of modules (Swenson 2013). However, the benefit from a tracking system will have to be weighed against the extra cost and upkeep of movable parts. This report will only handle fixed PV installations.

Method

The electric power production will be calculated using Homer, an energy modeling software for hybrid renewable energy systems, and weather data from an average year in Uppsala from

Meteonorm 5.1. Calculations will be made for a PV module of 150 W m^2 with 15 % efficiency at STC, the considered area is thereby 1 m^2. Nominal operating temperature is set to 47°, the temperature coefficient of power is set to - 0,5 %/°C, derating factor to 80 % and the albedo is set to 0,2 all year around. The placements of the module to be considered in the report will be azimuths of - 80°, - 40°, 0°, 40° resp. 80°, and tilts of 0°, 30°, 45° and 60°.

Results

Annual Variation in Production due to Placement

The optimal placing of the 150 W PV module, resulted in an electricity production of 143 kWh/yr. Table 1 and Figure 1 shows the deviations from this, due to different placements.

Table 1: The yearly variation in electricity production for different placement of PV modules. Reference placement is set to the overall optimum placement, 0° azimuth and 45° tilt.

Annual Production, Overall

		West		South		East
		80°	40°	0°	-40°	-80°
Tilt	60°	75%	90%	97%	92%	77%
	45°	80%	94%	100%	95%	81%
	30°	83%	94%	99%	95%	84%
	0°	-	-	84%	-	-
	30°+60°	79%	92%	98%	94%	81%

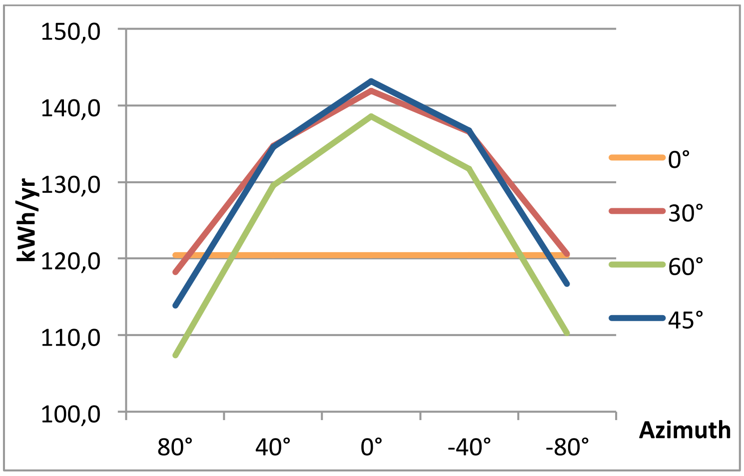

Figure 1: The yearly electricity production from the 150 W modules, in different orientations.

The result from this simulation shows that the tilt doesn't affect the yearly production by any larger amount. The azimuth, on the other hand, has a larger impact on the modules yearly production. At some point, it will be more advantageous to place the modules flat instead of in a large azimuth. Placing the modules to flat will however result in more problems with snow amassing on the modules, reducing production and increasing the risk of large snow-masses falling from the track. According to the report "Installationsgudie – Nätanslutna solcellsanläggningar" by Solelprogrammet (no date), placing the modules in < 33° tilt will result in losses of the yearly production by a few percent due to snow. Flat placement of the modules will require an effective method for maintenance and removal of snow.

As the PV modules will be used to feed the PRT system with electricity, it's interesting to see how the electricity production behaves during morning and evening rush-hours. For this reason the production data for morning-hours, 7-9 a.m. and evening-hours 3-5 p.m. where compared. The results can be seen in Table 2 and Figure 2 below.

Table 2: The yearly variation in electricity production during morning and evening hours, for different placement of PV modules. Reference placement is set to the overall optimum placement, 0° azimuth and 45° tilt.

Annual Production, 7-9 am

		West		South		East
		80°	40°	0°	-40°	-80°
Tilt	60°	37%	44%	95%	133%	139%
	45°	38%	54%	100%	131%	137%
	30°	47%	67%	101%	124%	128%
	0°	-	-	89%	-	-
	30°+60°	42%	56%	98%	128%	134%

Annual Production, 3-5 pm

		West		South		East
		80°	40°	0°	-40°	-80°
Tilt	60°	148%	137%	93%	43%	39%
	45°	145%	136%	100%	53%	40%
	30°	135%	128%	103%	68%	48%
	0°	-	-	94%	-	-
	30°+60°	141%	133%	98%	55%	43%

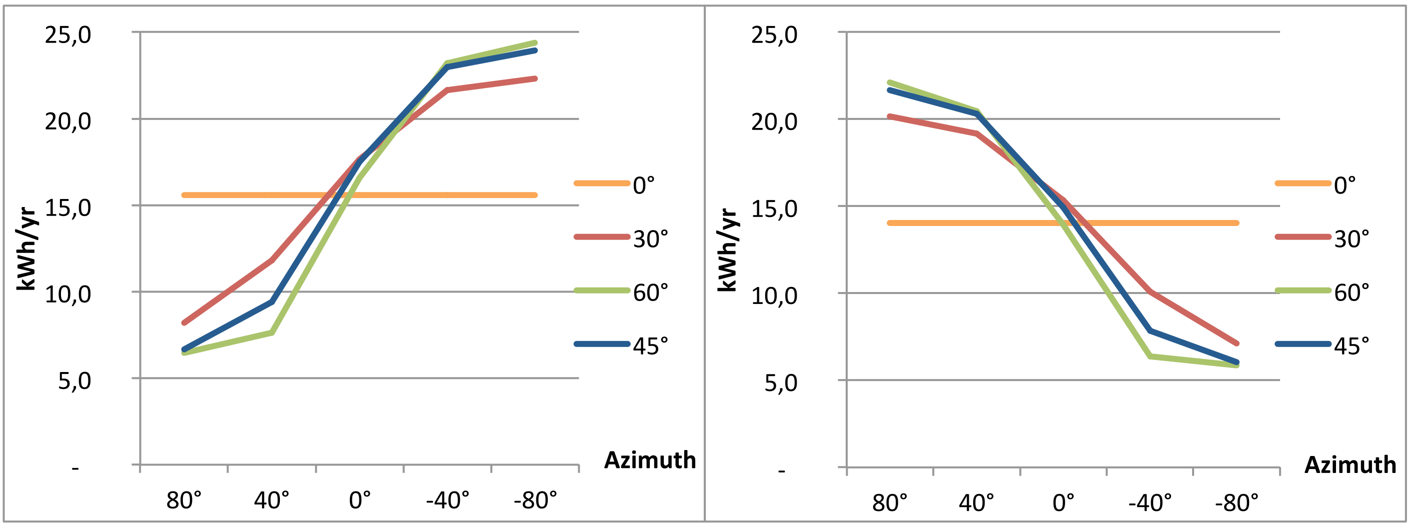

Figure 2: The yearly electricity production during morning and evening hours, for the 150 W modules, in different orientations, 7-9 a.m. left, 3-5 p.m. left.

The azimuth of the module plays a big role in the cell's efficiency during morning and evening hours. Facing the module with a high tilt in an eastward direction will produce more electricity during morning-hours. This is because the module will be more perpendicular to the sun during these hours. Depending on costs of buying and selling electricity and storage capabilities, it might not be a bad idea to place the module in a different azimuth. But the loss of production in the evening for an east-facing module is greater than the gain in the morning, reducing the annual production of the module.

Comparison of Modules Facing East and West or South

The azimuth of the PV modules running above the PRT track is unchangeable. This simulation analyzes the electricity production by modules divided equally in east and westbound directions. This is compared to the same capacity installed in a south-facing position. The annual difference is represented in Table 3 and Figure 3 below.

Table 3: The yearly variation in electricity production for different placement of PV-modules. Reference placement is set to the overall optimum placement, 0° azimuth and 45° tilt.

Annual Production, Overall

Tilt		Azimuth 0°	±40°	±80°
	60°	97%	91%	76%
	45°	100%	95%	80%
	30°	99%	95%	83%
	30°+60°	98%	93%	80%

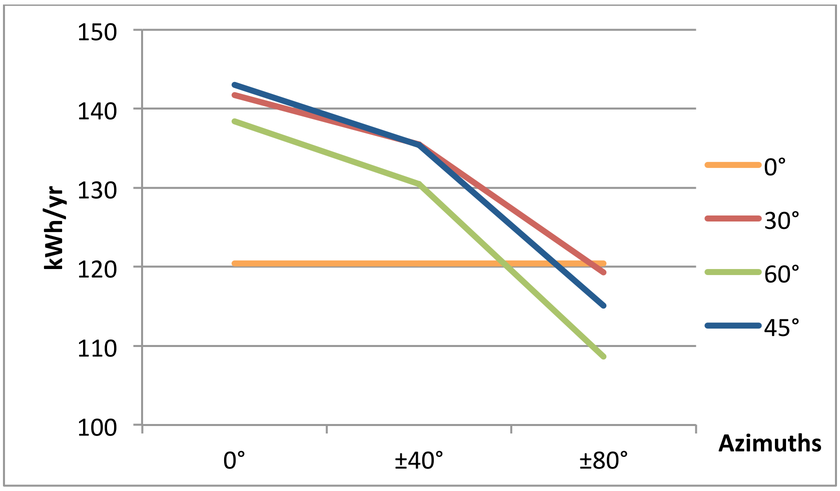

Figure 3: The yearly electricity production from the 150 W modules, in different orientations. In the case ±40° and ±80°, 75 W is placed in each azimuth.

As previously mentioned, facing the modules more to the east or west could increase the electricity production during morning respectively evening hours. Also mentioned was the fact that loss of production during the other part of the day exceeded the gain during the hours with improved production. Table 4 and Figure 4 sums up the electricity production of PV modules with the same capacity, installed facing south or divided between east and westbound direction, for morning and evening hours.

Table 4: The yearly variation in electricity production, during morning and evening hours, for different placement of PV modules. Reference placement is set to the overall optimum placement, 0° azimuth and 45° tilt.

Annual Production, 7-9 am				
		Azimuth		
		0°	±40°	±80°
Tilt	60°	95%	88%	88%
	45°	100%	93%	87%
	30°	101%	96%	87%
	30°+60°	98%	92%	88%

Annual Production, 3-5 pm				
		Azimuth		
		0°	±40°	±80°
Tilt	60°	93%	90%	93%
	45°	100%	94%	93%
	30°	103%	98%	91%
	30°+60°	98%	94%	92%

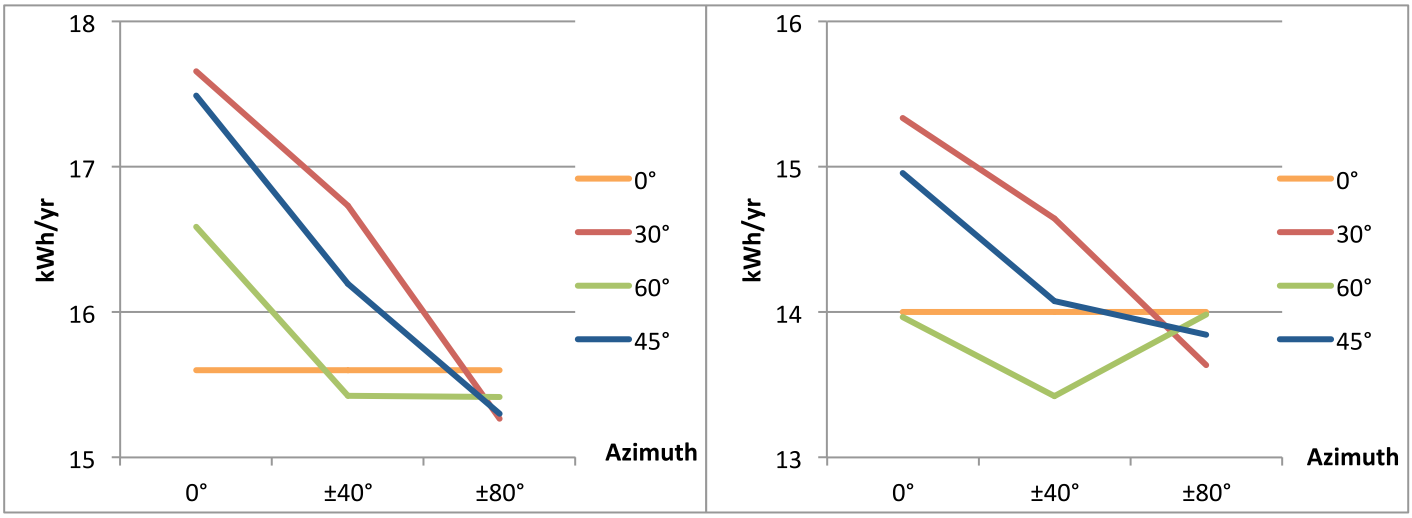

Figure 4: The yearly electricity production during morning and evening hours, for the 150 W modules, in different orientations, 7-9 a.m. left, 3-5 p.m. left. In the case ±40° and ±80°, 75 W is placed in each azimuth.

Facing the panels to the east or west will shift the peak production from noon and produce more electricity in the morning resp. evening, as shown in Figure 5 below.

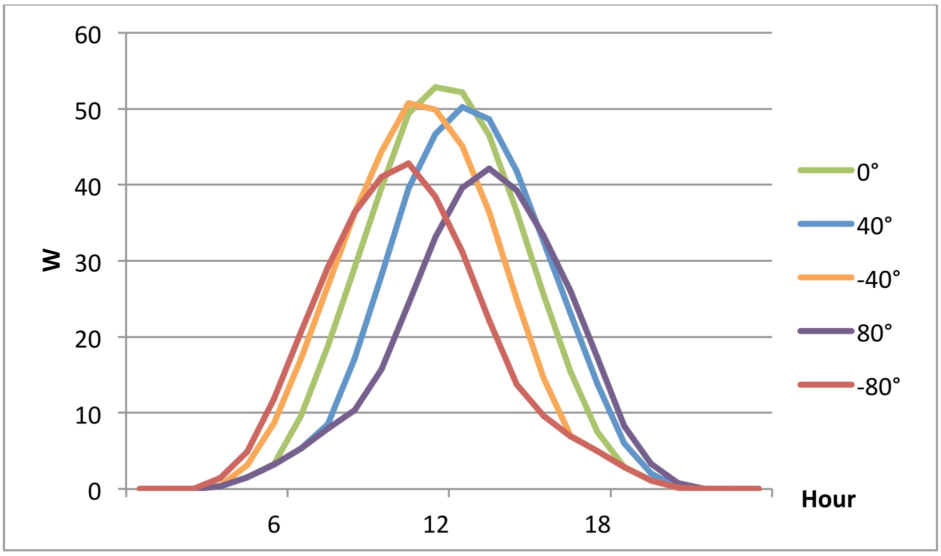

Figure 5: Average daily production of a 150 W PV module in different azimuths, tilt is set to 45° in all scenarios.

The PRT track will mostly allow for installments in azimuths around ±40°. The placement of modules in such a way gives higher efficiency in morning and evening hours, relative to overall efficiency. This will smoothen out the daily production curve from the modules, giving a larger portion of production in morning and evening hours as shown in Figure 6 below.

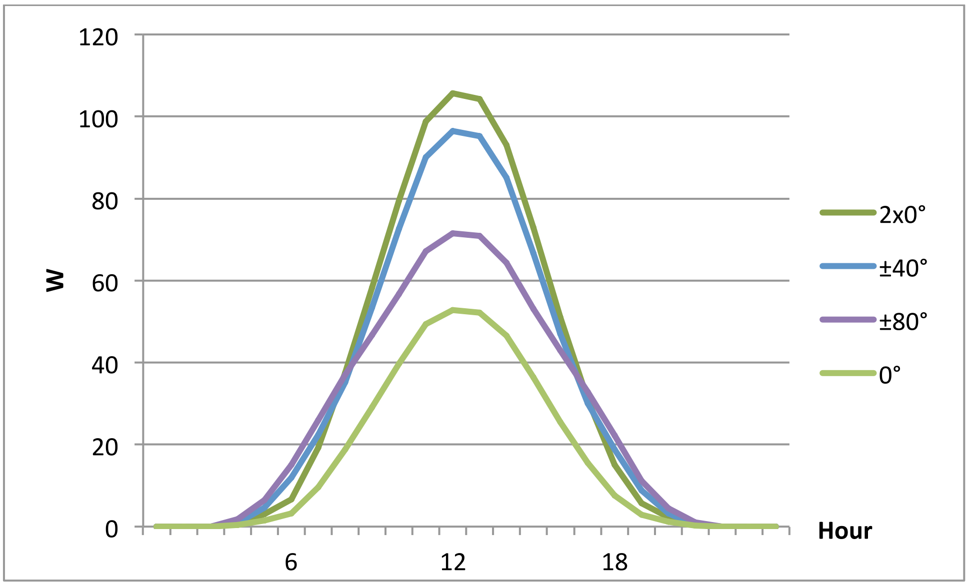

Figure 6: Average daily production of 2x150 W PV modules installed in 0° azimuth, compared to ±40° resp. ±80° azimuth. As a reference, the average daily production of a 150 W PV module installed in 0° azimuth is shown. Tilt is set to 45° in all scenarios.

If electricity demand is higher in the morning and evening than in mid-day, which is the case for the PRT system, the installment of PV modules in west or east-facing directions could be beneficial, depending on sell-prices and the capacity of the grid and/or storage capabilities.

References

Labouret, A.; Villoz, M. (2010), *Solar Photovoltaic Energy*, Institution of Engineering and Technology, chapter 2, p. 30-31

Solelprogrammet (no date), *Installationsguide – Nätanslutna solcellsanläggningar*,
http://solelprogrammet.se/Global/installationsguide_solceller.pdf?epslanguage=sv
Read 2013-05-16, p. 16

Swenson, Ron., INIST, *Comments re. solar tracking system,* 2013-05-22

Report X21

[Photovoltaics and Converters]

Authors: Joakim Björk, Christian Jansson, Hanna Jansson

2013-05-28

Underlying parameters of importance, such as the conditions of power supply and dimensions of the available grid electricity, and a description of system layout and components, such as PV modules and converters, used in different regions of the PRT system, are explained in this report. Additionally, basic economic calculations have been made, including subsidies and the cost of components for three different sized systems.

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Background

Because solar energy is an intermittent energy source, the PRT system needs to be supported by other energy sources as well. Therefore the system must be connected to the electricity grid in addition to the photovoltaic energy production. After consulting David Söderberg at Vattenfall, the system was decided to be installed as described below.

Connection to the Grid

The PRT system runs on a 750 V DC power supply and is connected to the high voltage city grid of Uppsala, meaning 50-30 MVA and 11-20 kV AC. This will be the PRT track's main supply source of steady power.

The electricity produced by the PV system will be transformed to 400 V AC in order to provide electricity for the low voltage internal consumption such as regulators and lighting at the stations. The excess electricity will be converted and used to supply the PRT track with 750 V DC, and the remainder will be fed into the main low voltage city grid of Uppsala as illustrated in Figure 1.

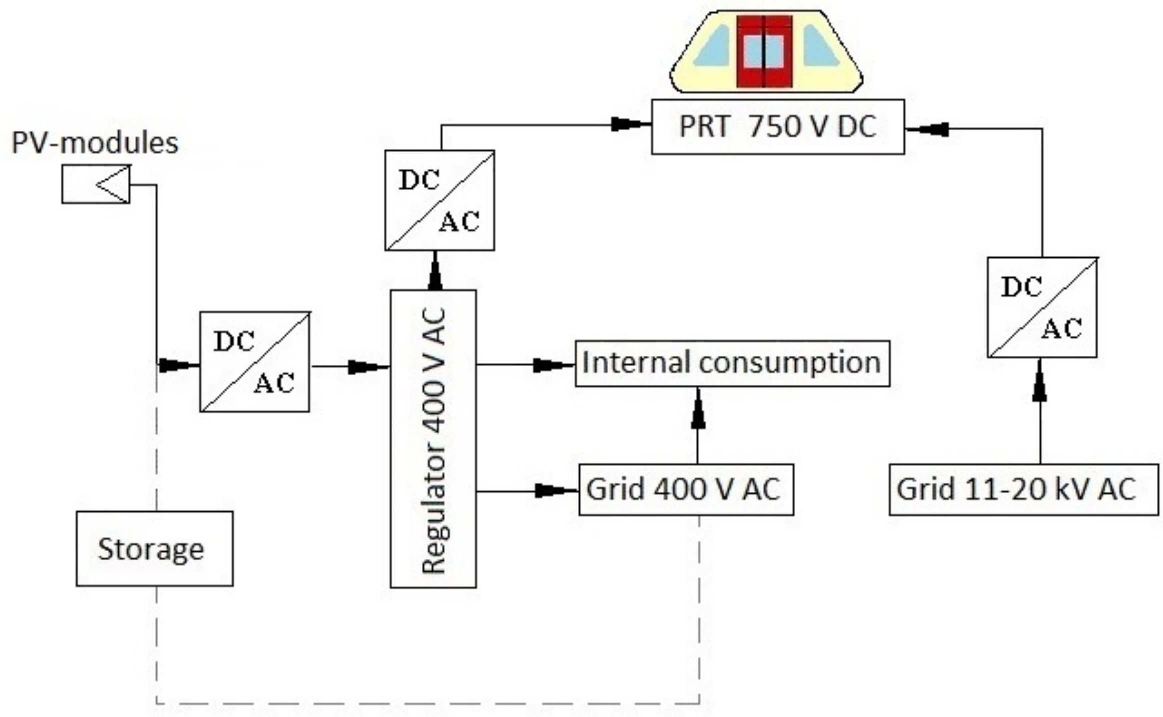

Figure 1: A schematic overview of the PRT's electrical system.

Components Used

Photovoltaic (PV)

The electricity producing components of the solar panel are the photovoltaic cells, which are composed of thin layers of semiconducting materials producing a voltage of 0,5 – 0,7 V when exposed to light. The most commonly used technology is crystalline silicon cells (Labournet, Villoz 2010). To increase voltage, a string of cells are connected in series. This will allow a higher power output while maintaining a low current, minimizing the ohmic losses through heating of the cells. The efficiency of a cell is also dependent on temperature because higher voltage levels are produced at lower temperatures. Conventional solar panels are produced as modules containing several strings connected in parallel. The maximum voltage from a cell is called open circuit voltage (V_{oc}) and the maximum current from a cell is called short circuit current (I_{sc}). To reach the maximum power output (P_{max}) of the cell, regulation is used to keep the output near the maximum power voltage and respectively current (V_{mp} and I_{mp}). The relation between these parameters can be seen in Figure 2 below, showing an IV-diagram of 36 silicon cells connected in series. These parameters vary for different technologies and are affected by conditions such as temperature, since higher temperature reduces V_{oc}, and the power of the incident light, as higher power increases I_{sc}.

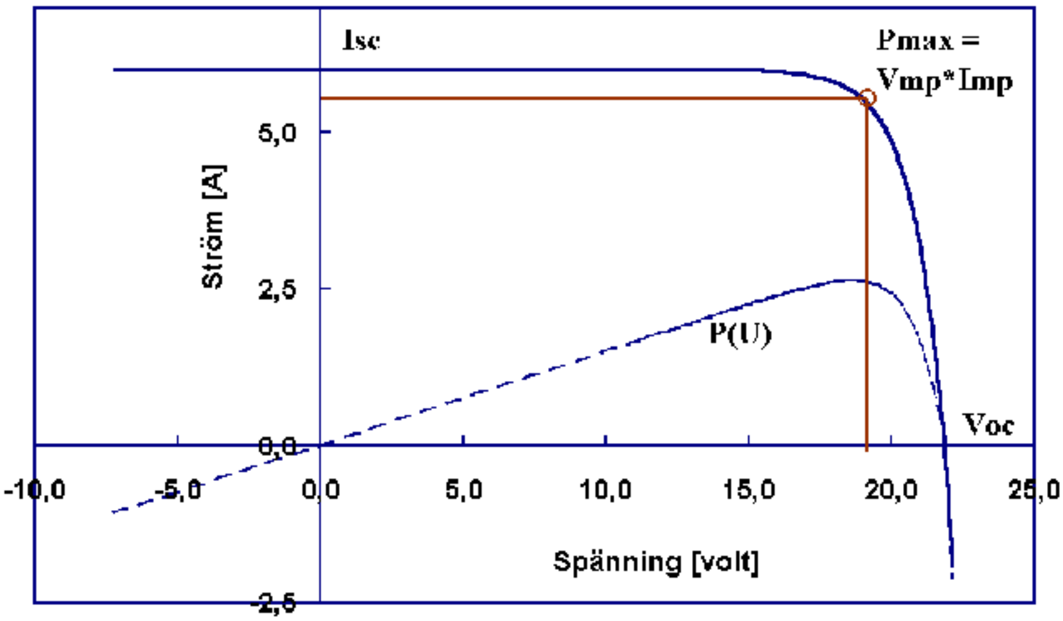

Figure 2: A diagram describing the voltage and current output of the cell. The maximum power point, MPP can easily be seen in this graph, which is called an IV-diagram. In this case, 36 cells are connected in series. (Solelprogrammet no date, a)

Converters

A converter can either be an inverter (converting DC to AC) or a rectifier (converting AC to DC). When designing the photovoltaic system it is important to match the modules with the chosen inverter. Strings of modules are connected in series, called PV arrays, in order to stay within the lower and higher operating voltage of the inverter. To reach the inverters rated power several strings may be connected on parallel to the input of the inverter. Effects from shadows need to be taken into account when connecting modules, or individual cells, in series. If a module in series is shaded the whole string loses output power. However, by using bypass diodes or solar maximizers, allowing the current to flow past the affected modules, losses can be reduced (Solelprogrammet (no date, a)). The output of the inverter is controlled by using a maximum power point tracker (MPPT), which varies the input voltage and current of the inverter and thereby allows the modules to work at their maximum efficiency. This control system may also be used if the output of the inverter needs to be lowered, thereby avoiding the excess power being dispersed as heat. The inverter may also be connected with a transformer on the AC-side, which helps in reducing harmonics and providing a galvanic isolation between the grid and the DC-system. Characteristics of an inverter are described in Figure 3 and 4 below.

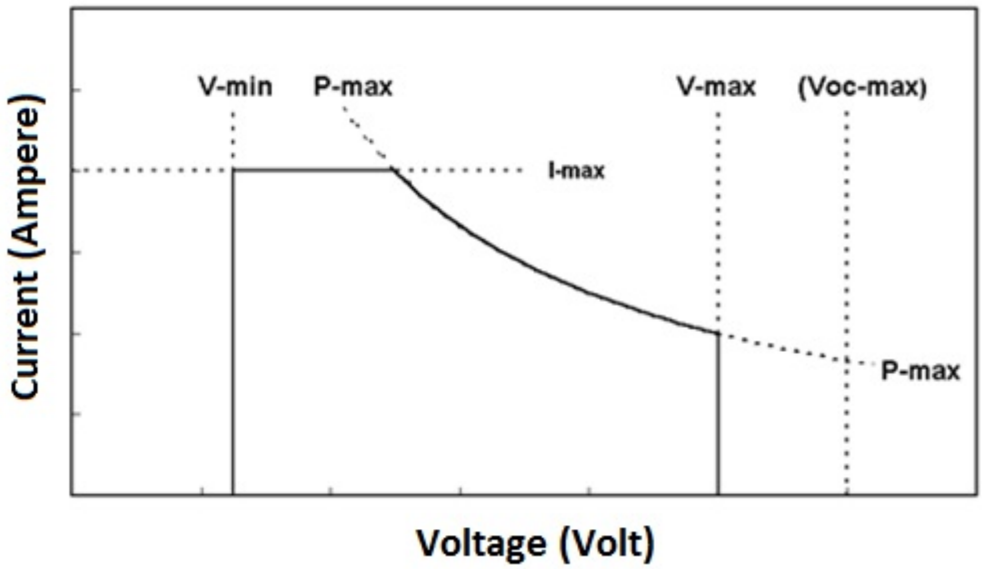

Figure 3: A diagram showing the working area of an inverter. The input from the connected modules needs to be inside the fully drawn line during operating conditions. (Solelprogrammet no date, b)

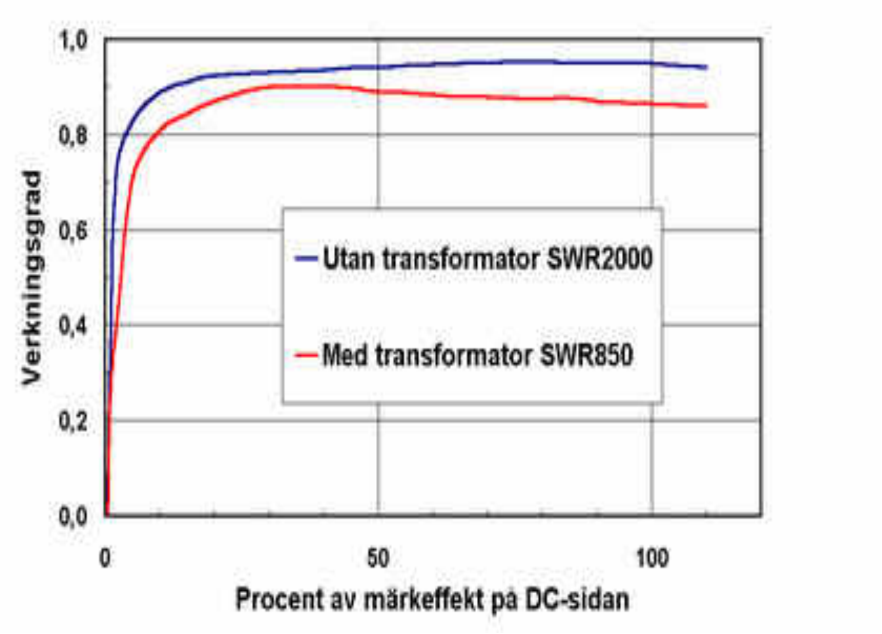

Figure 4: A diagram showing the efficiency of an inverter (blue line) and an inverter with a transformer on the AC side (red line). The efficiency is showed as a function of the rated power of the inverter. (Solelprogrammet no date, c)

Economic Calculations

Module Prices

In order to roughly estimate the costs of the PV systems, recent installations have been regarded and publications about price development earlier years have been looked into. Prices for PV systems are primarily compared by costs per watt peak, W_p, which is the maximum power produced by the cell at standard conditions.

The module prices in Sweden have been decreasing at rapid speed during the last couple of years, following the development at the world market (Solelprogrammet 2011). The prices will most likely continue to fall but not as rapid as they recently have (Zimmermann 2013). According to Johan Lindahl, Department of Engineering Sciences at Uppsala University, the standard module price for 2012 was 16 SEK/W excl. VAT, which will be used when calculating the costs of the specific PV system used at the PRT-system. Included in the price are costs for the photovoltaics, module installation and the converters required.

Subsidies

Since 2009 a government grant is available for installations of PV systems. At 2013 – 2016 the subsidy will be set to 35% of the installation costs with a maximum of 1,2 million SEK, not to exceed 37 000 SEK excl. VAT, per installed kW electrical maximum effect. The grant is available for both private actors and companies (Swedish Energy Agency 2013).

System Costs

The costs for installing the three different scenarios are presented in Table 1. The maximum levels of subsidies are reached for all scenarios.

Table 1. Economic calculations for the three different scenarios.

Event	**Installed kWp**	**Cost, SEK**
Scenario A	1 670	26 720 000
Subsidies		-1 200 000
Balance		**25 520 000**
Scenario B	2 420	38 720 000
Subsidies		-1 200 000
Balance		**37 520 000**
Scenario C	1 040	16 640 000
Subsidies		-1 200 000
Balance		**15 440 000**

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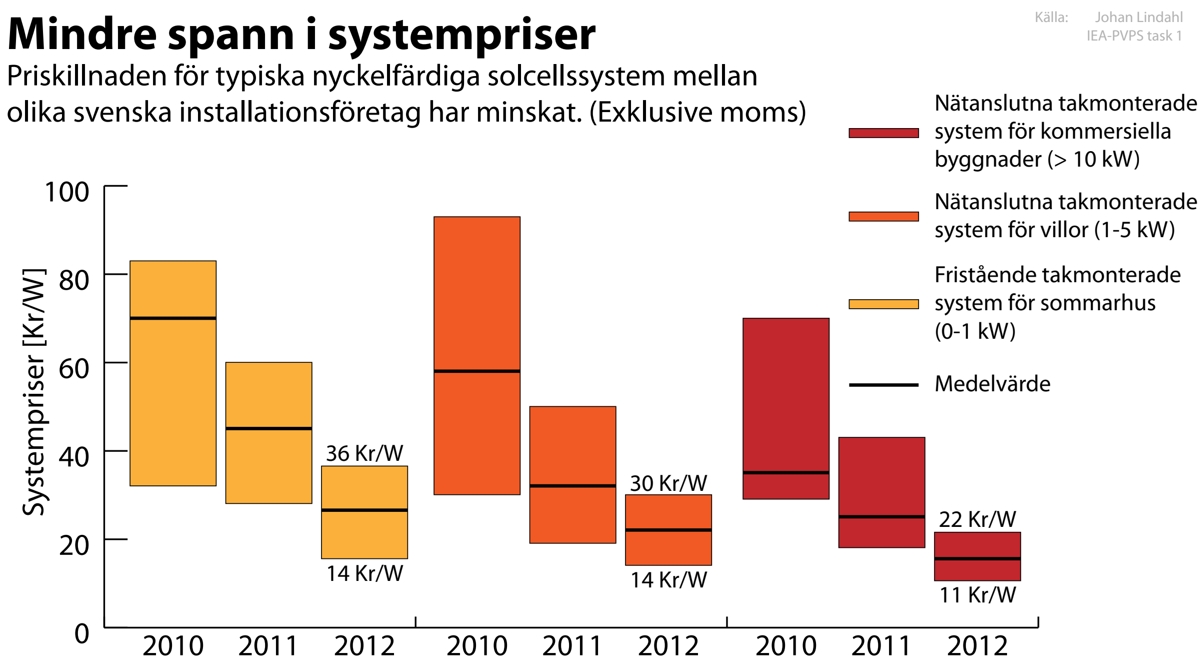
Appendix 1- Mail from J. Lindahl 2013-05-06

Hej Hanna,

Systempriserna i Sverige varierar utifrån vilket sorts system och vilken leverantör man pratar med. Det som olika leverantörer ser som typiska priser för större system ligger mellan 11 och 22 kr per W exklusive moms (Se bifogad graf). För att få en mer exakt kostnad så behöver man kontakta olika leverantörer och be om offerter för projektet.
Priserna för endast konverterare har jag tyvärr inte någon koll på.

Mvh
Johan



SOLAR SKYWAYS

Report X22

[Travel Simulation in Arena]

Authors: Björn Isaksson, Erik Lindholm

2013-05-28

A model of the PRT system was created, in the simulation software Arena, in order to estimate the total power consumption of the system. Assumptions based on travel patterns, calculations and simulation results have been analysed and are presented in this report. Two different energy consumption scenarios, 1 356 MWh and 1 907 MWh per year, were the end result.

Table of Contents

Method

To make a good estimation of the planned PRT system, a model was built in the simulation software program called Arena. The model consists of the ten planned stations and the tracks with precise distances between them. Travellers are created at different stations, according to the results accomplished in sub-report X11 - Travel Pattern Estimations, and a request is made for a podcar to come to the station and take the traveller to its desired destination. The model was used to estimate the number of podcars required to meet system needs and to predict the energy consumption of the system.

Simulation Construction

What follows is a brief summary of how the Arena model is constructed, consisting of stations that create travellers, the network that connects the stations and the podcars transporting the travellers through the network. A picture of the model can be seen in Appendix 2.

Station

The station creates travellers according to a schedule, which is based on the estimated travel flows, and assigns them with their destination. If more than one traveller wants to travel to a specific destination, the traveller first in line requests a podcar to the station. The other travellers get in line waiting for the requested podcar to arrive. The travellers in line (up to five) are then transported through the network to their destination, where they exit the podcar and leave the station. If there are any travellers left when the podcar leaves the station, the traveller first in line will request a new podcar.

Network

The network simulates the tracks and consists of unidirectional paths which is connected to the stations and assigned with their approximate distances.

Podcar

A podcar is a passive resource. When requested it moves to the specific station and transports the travellers to their destination. It is given characteristics such as speed, length and acceleration according to one of the main manufacturers (Vectus 2007).

Control System

The control system on an actual track will be essential; however, in the model there is a limited or no control system. In certain cases, a limited control system is used to avoid queues, but that is clearly stated in the different cases. If nothing else is clearly stated, each traveller simply requests the closest podcar, which after travel, goes to the nearest boarding platform.

Sensitivity Analysis

Estimation Sensitivity

Analyses of three scenarios were done in order to estimate how sensitive the model is to estimations of traveller's destinations and starting points. The first scenario was the one-way-scenario (OWS), the second scenario was the scattered scenario (SS), which requires a limited control system[1], and the third scenario was the two-way scenario (TWS). In OWS, 69% of the travellers travel from the central station to the hospital, Science Park and BMC. The rest of the travellers are more or less evenly scattered between the other stations (see Table 1). In SS, the travellers starting points are more evenly distributed (see Table 2). In TWS, 36% of the travellers travel from the central station to other stations and an equal number of travellers are head in the opposite way while the rest of the travellers are scattered evenly across the system (see Table 3). The travellers are created according to normal distributions where the standard deviation (std) is half the expected value and first creation time[2] is the inverse of the expected value divided by four. For example, if the expected value is 6 travellers every hour at a station, an average of ten minutes between each traveller is expected and therefore the first traveller creation time is 2.5 minutes. Table 1-3 in Appendix 1 shows how the expected values in normal distributions are divided among the stations. In all three scenarios, the total number of the expected values is 528 passengers per hour.

Simulations were done for the three scenarios OWS, SS and TWS for 30, 35 and 40 podcars in the system, giving a total of nine simulations. Each of those nine simulations was done ten times to make sure no coincidences affected any simulation more than the others. Values presented are averages of the ten simulations that were done for each scenario. On the following page, Figure 1 illustrates the summarized results of these simulations, where the average total travel time is the average time spent in podcars and average time spent waiting for a podcar. Relative power consumption is shown in per cent depending on how many additional pods were required (driven, both with travellers and empty) on an average basis. The podcars were utilised between 86% and 97% in these cases; less utilisation for more pods on the same scenario. Figure 1 shows that there was no significant reduction in travel time if the number of pods in the system increases. For approximately 500 travellers, a podcar utilisation at 90-95% is therefore sufficient.

The same analysis was performed for 90 travellers, this time with 12, 16 and 20 podcars. Figure 2 on page 3 shows the result of these simulations. The pods were utilised between 62.5 and 83% in these scenarios. There is a clear trend in Figure 2, but since the travel time is more or less constant and the waiting time can be decreased with a control system, the time savings travellers will be able to do in an actual system with an increased number of pods will be limited compared to an increase in power consumption. It was therefore assumed that about 80% is a reasonable pod utilisation for 90 passengers.

[1] In both SS scenarios approximately half of the pods that travel to station 5-7 (the hospital) are sent to station four or ten to avoid traffic jams on the loop around the hospital

[2] First creation time is the time when Arena creates the first traveller and starts to follow the normal distribution for every other passenger.

Comment on Control Systems

The control system used in the actual system will reduce the waiting time since pods will already be placed where the next traveller is most likely to be, rather than where the last traveller left the system. This will probably not affect the energy consumption to the same extent since each podcar has to travel the actual distance anyway. Therefore the travel time in an actual system will be less than in these examples (especially in cases with few pods since the probability for any podcar to be nearby decreases) and the energy consumption will be described as more accurate.

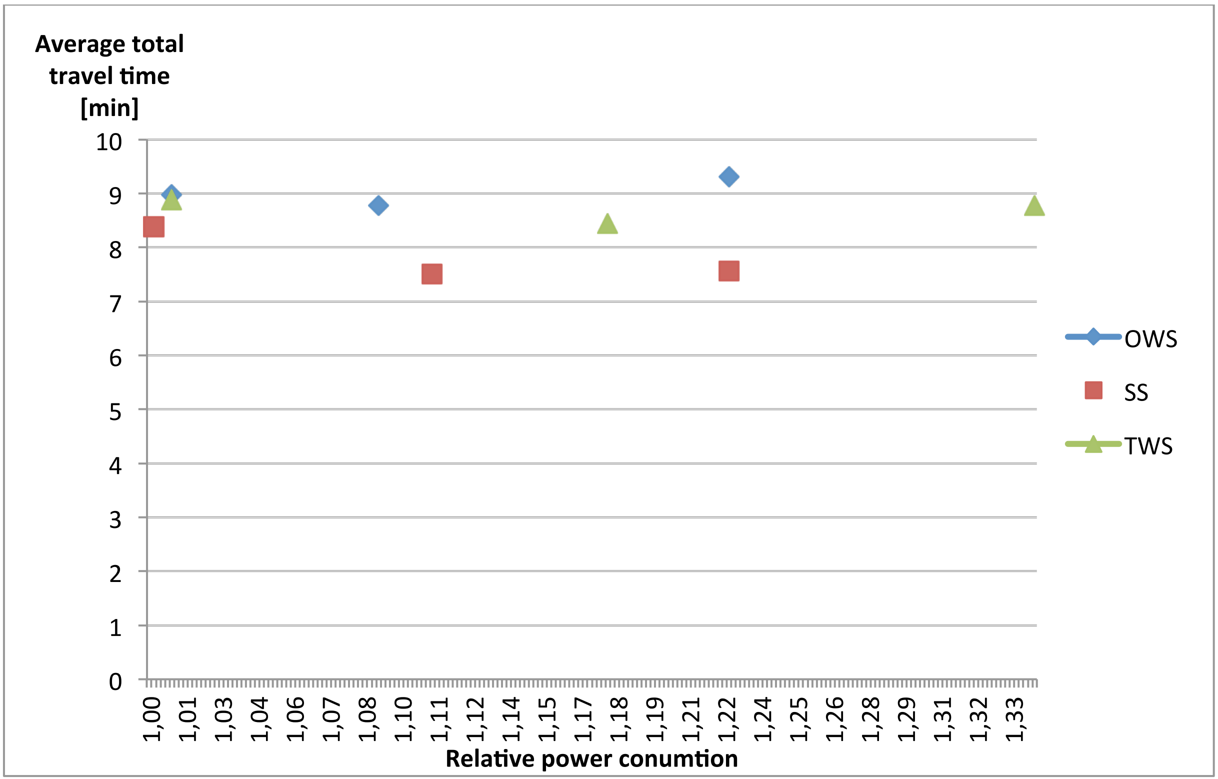


Figure 1. Sensitivity analysis, 528 passengers.

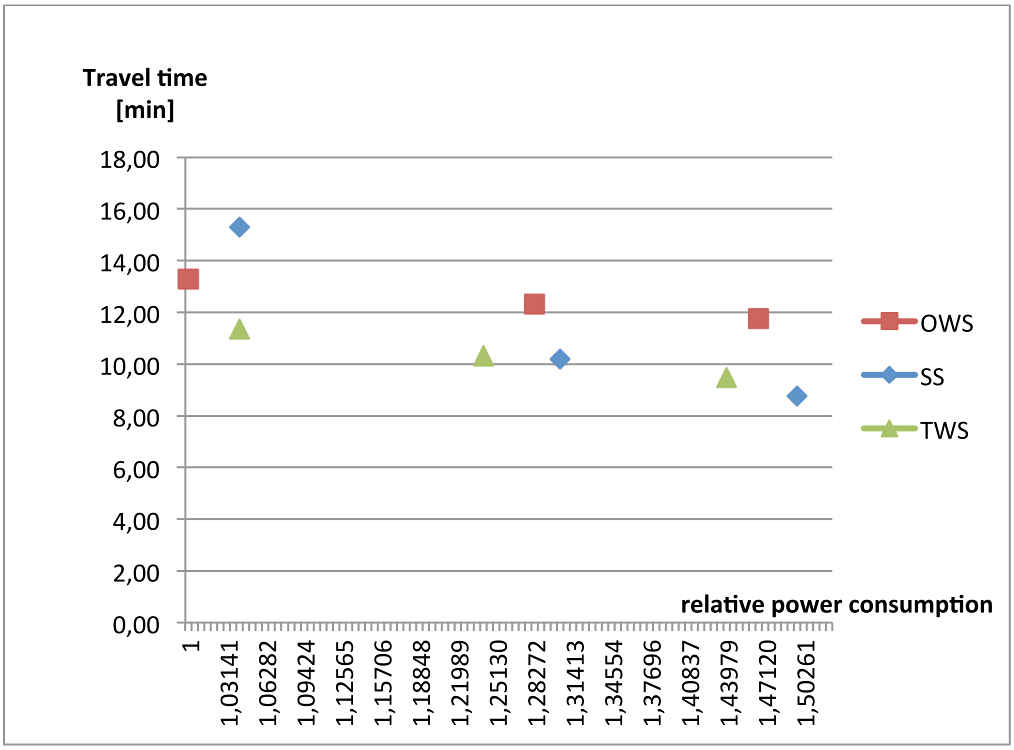


Figure 2. Sensitivity analysis, 90 passengers.

Annual Energy Consumption (EC)

According to the travel estimations, done in sub-report X11 – Travel patterns estimation, for a typical weekday, simulations were done in Arena. Thereafter, a typical weekend day was created by making the curve smoother and displacing some of the morning rush hour to later hours. According to assumptions in sub-report X11, the number of travels will be reduced to about 60% of a regular weekday, which was accomplished by reducing total energy consumption during the day to 78% of a weekday. The reason energy consumption is not lowered as much as the traveling flows is that the number of podcars are not directly proportional to the number of travellers and that the energy consumption of the control system and stations are more or less unaffected by changes in travel flows. Finally, a vacation day was made by creating an average of a weekend and weekday.

The estimations done are shown in Figure 3 and 4 on page 5. Two cases were calculated; the low case scenario where the podcars power consumption are about the same as the podcar system at Heathrow in London, and a high case scenario where the power consumption in a driving podcar is increased by 50%. Information about the podcars energy consumption was received from B. Gustafsson via email dated 2013-04-12 (see Appendix 3).

Finally, a full year was created by combining weekdays and weekend days to normal weeks and by creation of vacation weeks in week number 1 (Christmas holidays), 8 (Sports holidays), 14 (Easter holidays), 24-33 (summer holidays), 44 (autumn holidays) and 52 (plus one day to create a year of 365 days) (Christmas holidays). Figure 3 and 4 illustrate the average hourly consumption calculated in Arena. Figure 3 is the low case scenario and Figure 4 the high case scenario.

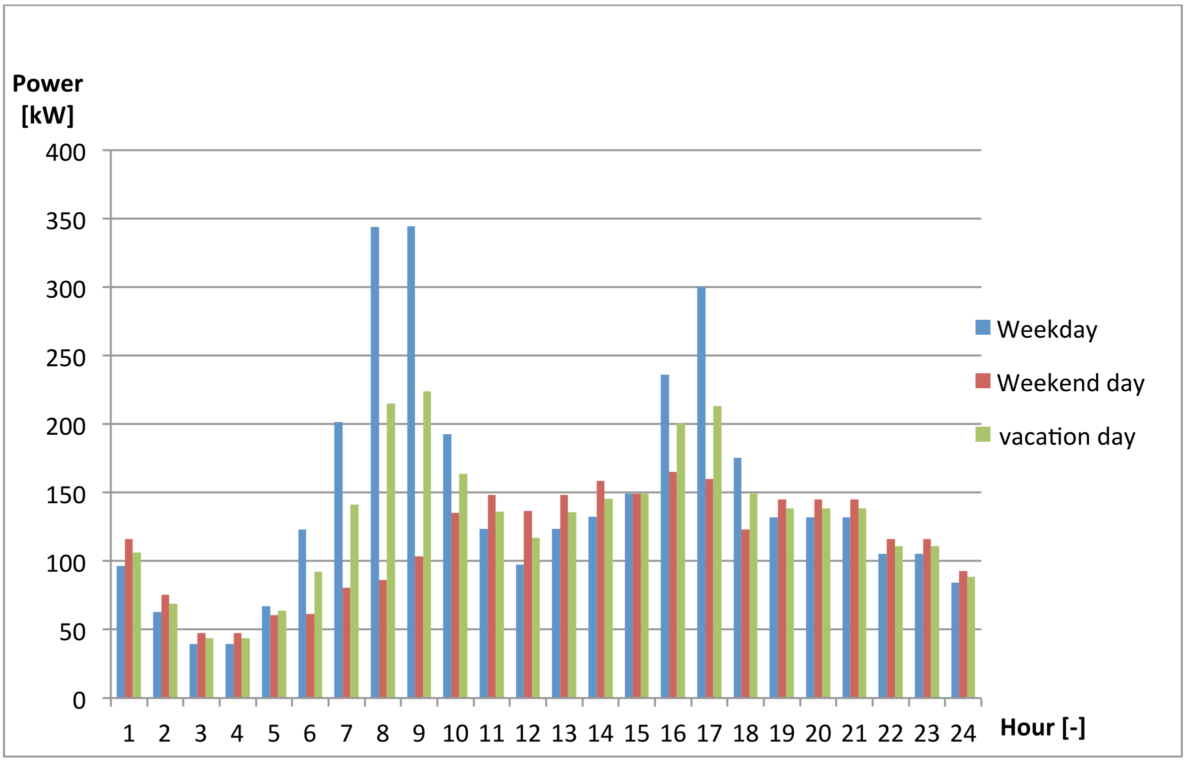


Figure 3: Average hourly power consumption during the three typical days, Low case scenario.

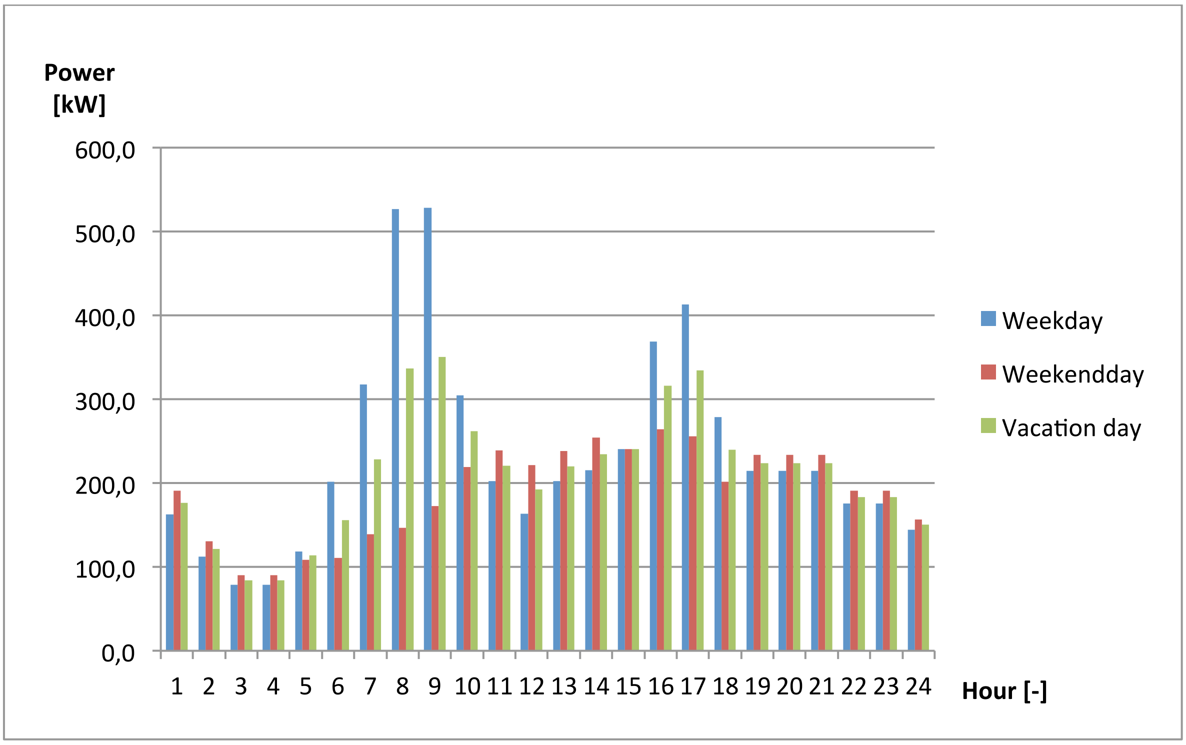


Figure 4: Average hourly power consumption during the three typical days, high case scenario.

Results

Figure 5 shows monthly energy consumption of the PRT system, resulting in the annual energy consumption of 1 356 MWh (low case, Scenario A & C) and 1 907 MWh (high case, Scenario B).

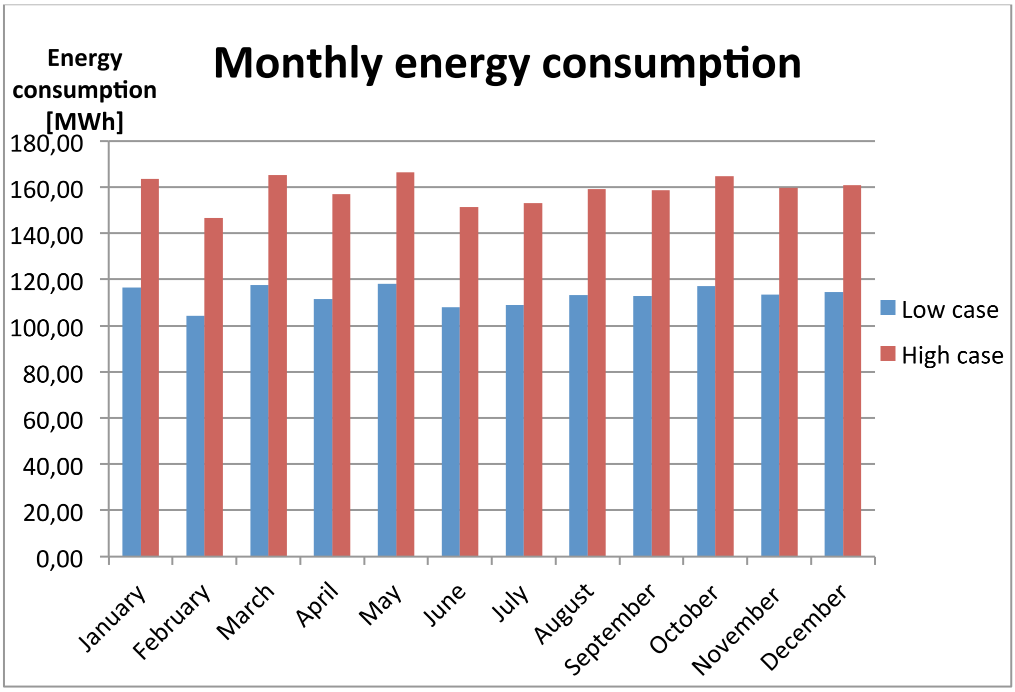


Figure 5: Monthly energy consumption for the two cases.

Table 1 and 2 show key Figures from simulations; power consumption (PC) and part of the yearly energy consumption. The simulations have a resolution of one hour.

Table 1: Data used in the energy consumption calculations.

Energy consuption	Low case	High case
Driving podcar [kWh/km]	0,10	0,15
Idle podcar [kW]	0,40	0,4
Station power [kW]	10	10
Control system, maintainance [kW]	10	10

Table 2: Assumed values and key figures, low case/high case.

	Driving (40 km/h; 0,1/,15 kWh/km + 400 W heating and cooling) [kW]	Idle (Computers, heating, cooling) [kW]	Part of yearly energy consumption [-]
Podcar PC	4,4/6,5	0,5/0,5	0,87/0,91
	Lighting, doors etc [kW]		
Stations PC	10/10		0,065/0,045
	[kW]		
Maintenece, control system EC	10/10		0,065/0,045
Average PC [kW]	158,2/217,7		
Max PC [kW]	364,5/528,5		
Min PC [kW]	59,7/78,4		

Comments on Results

The simulations were done to estimate the entire system power consumption. Relevant assumptions that were done were overestimated rather than underestimated to assure that the power consumption would not be too low. For example, a podcar is utilised as soon as it enters a station, even though it is not driving. A podcar that is utilised is assumed to drive at an average speed of 40 km/h, even though that is close to the maximum speed of 45 km/h. This results in a higher energy consumption since the podcar producers specify that the power consumption for a podcar is dependent on an average kWh/km rather than as average kW.

Variations in travel patterns dependent on seasons have not been not been taken into consideration, the exception of lower travel in summertime, due to vacations. Uppsala, like many other Swedish mid-sized cities, has a relatively compact and small city area. Therefore, many people use their bike, or walk as transportation during the summer when the weather is mild. However, in wintertime, weather conditions are less comfortable which may result in a higher utilization of a PRT system. An increased usage of public transportation during winter season has been confirmed by Anders Bergqvist at UL (2013), which may be a reason to encourage further investigation.

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Bergqvist, A., analyst at UL, *Conversation re. travel patterns in Uppsala city,* 2013-05-24

Appendix 1 – Sensitivity Analysis Tables

Table 3. 528 SS travellers distributions

	SS Station	From										Total to
		1	2	3	4	5	6	7	8	9	10	
	1	x	1	10	8	6	8	5	12	3	12	65
	2	2	x	3	3	5	6	3	4	10	4	40
	3	3	1	x	5	8	4	4	5	5	5	40
	4	3	3	1	x	5	6	5	6	6	3	38
To	5	12	10	6	6	x	8	6	12	4	10	74
	6	8	8	5	5	6	x	5	5	10	8	60
	7	10	6	8	8	6	6	x	3	8	5	60
	8	4	6	5	5	5	6	5	x	12	10	58
	9	6	5	6	6	3	5	3	4	x	5	43
	10	8	3	5	5	4	3	5	12	5	x	50
	Total from	56	43	49	51	48	52	41	63	63	62	528

Table 4. OWS 528 travellers distribution

	OWS Station	From										Total to
		1	2	3	4	5	6	7	8	9	10	
	1	x	1	2	3	1	2	3	1	2	3	18
	2	1	x	3	1	2	3	1	2	3	1	17
	3	2	2	x	2	3	1	2	3	1	2	18
	4	3	3	1	x	1	2	3	1	2	3	19
To	5	60	1	2	3	x	3	1	2	3	1	76
	6	60	2	3	1	2	x	2	3	1	2	76
	7	60	3	1	2	3	1	x	1	2	3	76
	8	60	1	2	3	1	2	3	x	3	1	76
	9	60	2	3	1	2	3	1	2	x	2	76
	10	60	3	1	2	3	1	2	3	1	x	76
	Total from	366	18	18	18	18	18	18	18	18	18	528

Table 5. TWS 516 travellers distribution

	TWS Station	From									
		1	2	3	4	5	6	7	8	9	10	
	1	x	1	2	3	30	30	30	30	30	30	186
	2	1	x	3	1	2	3	1	2	3	1	17
	3	2	2	x	2	3	1	2	3	1	2	18
	4	3	3	1	x	1	2	3	1	2	3	19
To	5	30	1	2	3	x	3	1	2	3	1	46
	6	30	2	3	1	2	x	2	3	1	2	46
	7	30	3	1	2	3	1	x	1	2	3	46
	8	30	1	2	3	1	2	3	x	3	1	46
	9	30	2	3	1	2	3	1	2	x	2	46
	10	30	3	1	2	3	1	2	3	1	x	46
		186	18	18	18	47	46	45	47	46	45	516

Table 6. SS 90 travellers distribution

SS Stations	From										
	1	2	3	4	5	6	7	8	9	10	Total
1	x	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	4,5
2	0,5	x	1	1	1	1	1	1	1	1	8,5
3	1	1	x	1,5	1,5	1,5	1,5	1,5	1,5	1,5	12,5
4	1,5	1,5	1,5	x	0,5	0,5	0,5	0,5	0,5	0,5	7,5
5	0,5	0,5	0,5	0,5	x	1	1	1	1	1	7
6	1	1	1	1	1	x	1,5	1,5	1,5	1,5	11
7	1,5	1,5	1,5	1,5	1,5	1,5	x	0,5	0,5	0,5	10,5
8	0,5	0,5	0,5	0,5	0,5	0,5	0,5	x	1	1	5,5
9	1	1	1	1	1	1	1	1	x	1,5	9,5
10	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	x	13,5
Total	9	9	9	9	9	9	9	9	9	9	90

Table 7. OWS 90 travellers distribution

OWS Stations	From 1	2	3	4	5	6	7	8	9	10	Total
1	x	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	4,5
2	0,5	x	0,5	0,5	0,5	0,5	1	0,5	0,5	0,5	5
3	1	0,5	x	0,5	0,5	1	0,5	0,5	0,5	0,5	5,5
4	1	0,5	0,5	x	0,5	0,5	0,5	0,5	0,5	0,5	5
5	8	0,5	0,5	0,5	x	0,5	0,5	0,5	0,5	0,5	12
6	8	0,5	0,5	0,5	0,5	x	0,5	0,5	0,5	0,5	12
7	8	0,5	0,5	0,5	0,5	0,5	x	0,5	0,5	0,5	12
8	6	0,5	0,5	0,5	0,5	0,5	0,5	x	0,5	0,5	10
9	8	0,5	0,5	0,5	0,5	0,5	0,5	0,5	x	0,5	12
10	8	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	x	12
Total	48,5	4,5	4,5	4,5	4,5	5	5	4,5	4,5	4,5	90

Table 8. TWS 90 travellers distribution

TWS Stations	From 1	2	3	4	5	6	7	8	9	10	Total
1	x	0,5	0,5	0,5	4	4	4	3	4	4	24,5
2	0,5	x	0,5	0,5	0,5	0,5	1	0,5	0,5	0,5	5
3	1	0,5	x	0,5	0,5	1	0,5	0,5	0,5	0,5	5,5
4	1	0,5	1	x	1	0,5	0,5	0,5	0,5	0,5	6
5	4	0,5	0,5	1	x	0,5	0,5	0,5	0,5	0,5	8,5
6	4	0,5	1	0,5	0,5	x	0,5	1	0,5	0,5	9
7	4	1	0,5	0,5	0,5	0,5	x	0,5	0,5	0,5	8,5
8	3	0,5	0,5	0,5	0,5	0,5	0,5	x	0,5	0,5	7
9	4	0,5	0,5	0,5	0,5	0,5	0,5	0,5	x	0,5	8
10	4	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	x	8
Total	25,5	5	5,5	5	8,5	8,5	8,5	7,5	8	8	90

Appendix 2 – The Arena model

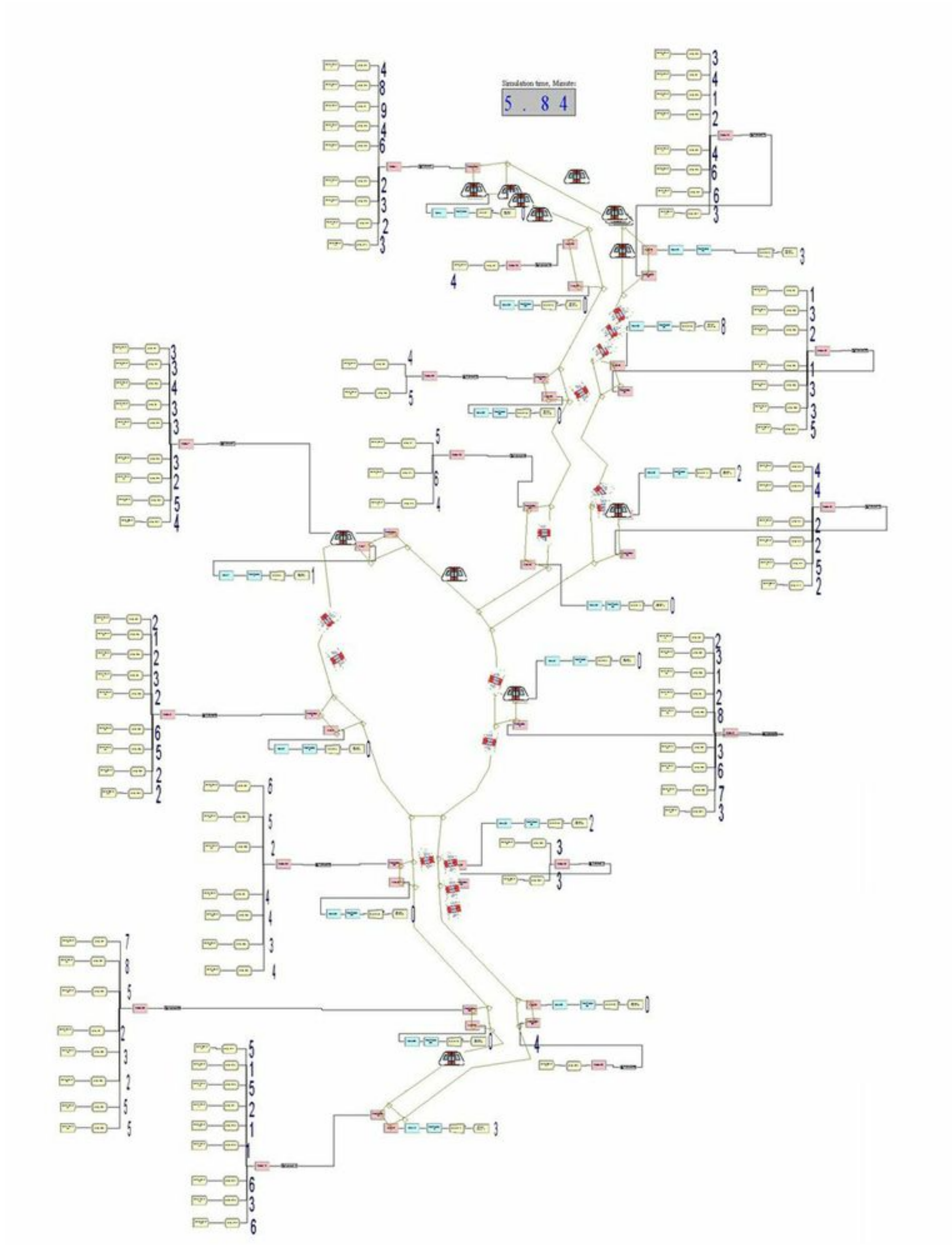

Figure 6: The model built in Arena

Appendix 3 – Mail from B. Gustafsson 2013-04-12

Jag undrar om du har några uppgifter på vad en vagn av den storleken skulle kunna dra för effekt vid körning, samt vid tomgång och även då motorn är avstängd (då med avseende på kylning/värme). Behöver man ens tänka på tomgångskörning i och med att det är elmotorer eller stängs motorn av helt vid stillastående?

Vi räknar med att Beamways vagn kommer att dra ca 0.05 kWh per kilometer tack vare ett optimerat drivsystem. ULTra har drivning via bilhjul och drar därmed ca 0.1 kWh/km medan Vectus, med linjärmotorerna som krävs för säker drift i snö drar 0.25 kWh/km enligt deras egna uppgifter.

Mycket riktigt drar inte en elmotor ström när man står still, förutsatt att det finns en parkeringsbroms som inte drar ström vilket är möjligt. Då kostar det bara kanske 100 W att hålla igång datorer och så vidare.

Kylning och värmning kan dra en hel del, och därför tänker Beamways isolera vagnarna noga, t ex. med tvåglasfönster. Vi hoppas komma till ett läge där vi klarar oss med 1 kW märkeffekt på värmesystemet och kanske 300-500W i snitt.

Vilken kapacitet i form av uteffekt och energi behövs i batterierna i vagnarna?

Beamways och Vectus har strömskena vilket gör att endast ett litet batteri för att ta sig till närmaste station vid strömavbrott krävs. Ca 1 kW vilket idag väger 10 kg. ULTra däremot kör med batteridrift och då kan det krävas rejäla batterier. Det har jag inte så mycket uppfattning om och det beror ganska mycket på hur snabbt de går att ladda på stationerna. Man måste väl ändå tänka sig att man ska ha tillräcklig energi i batteriet för att klara en rusningstid, dvs. kanske 2 timmar i full drift. Det torde då röra sig om ca 10 kWh, men det får ni väl räkna på.

Jag undrar även om du har några siffror på vad stationshusen kan tänkas förbruka. Då menar jag små hus byggda endast för ändamålet att ta emot dessa vagnar.

En stor fördel med spårtaxi är att man normalt inte väntar särskilt länge på stationerna. Det gör att intresset för klimatstyrning i stationerna minskar. Därför borde effekten för att driva en station begränsas till lite belysning nattetid samt lite datorer och mekanismer för dörrar etc. Borde gå att komma ner till kanske 1 kW.

Jag undrar helt enkelt över hur man bör räkna på energiförbrukningen i systemet och om du även har siffror på något som jag glömt fråga om ovanför skulle jag bli väldigt glad om du även ville dela med dig av dem.

Det kommer att tillkomma en del för underhålls/städnings-stationen och kontrollrummet. Ni kan säkert få fram siffror på den typen av anläggningar.

Report X23

Dimensioning the Photovoltaic System

Authors: Carl Näslund, Joakim Björk

2013-05-28

This report will handle system design including sizing, choice of solar cells, inverter and layout. PVsyst photovoltaic software was used to model the shading environment and electricity production of the PV system. Simulations in the program were done to estimate the efficiency and production from designated parameters and three different energy production systems were designed to match two different energy demands.

Table of Contents

PVsyst

PVsyst is simulation software that enables design and data analysis of photovoltaic systems. In order to reach designated production of the photovoltaic system, multiple simulations were done in the software program. By using the planned route in Introduction of PRT in Uppsala (Hunhammar, Lindström 2011a), Eniro, Google maps and physical measurements, a scale model was designed in PVsyst. Different segments of the podcar track were simulated separately in smaller sub-models in order to determine productivity and relevance to the system.

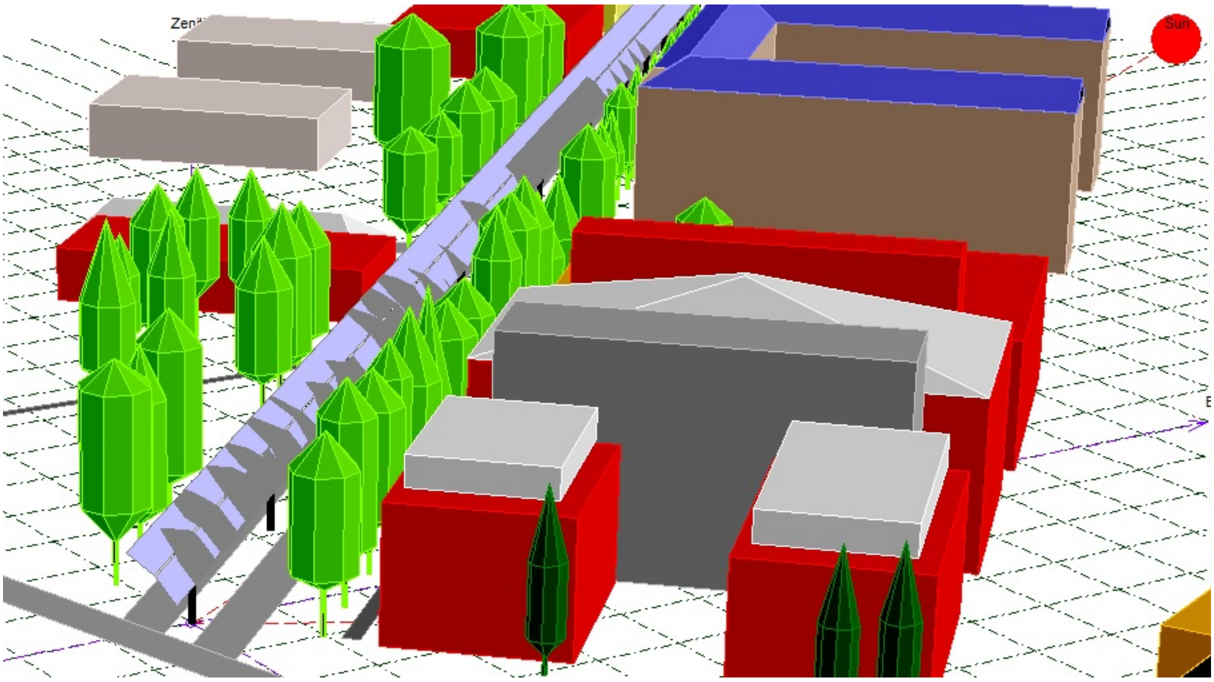

Figure 1: View of the simulation of Strandbodgatan in PVsyst.

Solar Panels Tilt and Orientation

Primarily the photovoltaic system needed to be designed to fit appropriate dimensions. Additionally, the lowest part of the solar panel was set to 7 meter above ground height because of clearance height issues. This is the lowest possible placement, giving a high estimation of shading losses. The solar panel along the track was chosen to be a heterogeneous system meaning that the solar panel is split into two segments with different tilts, each part with the width of 3.65 meters. The lower part of the solar panel has the tilt angle 55^o and the upper part has the tilt 35^o. A comparison was made between having a single fixed tilted plane system with the tilt 45^o and a heterogeneous system with the tilts 35^o and 55^o evenly distributed amongst the available area.

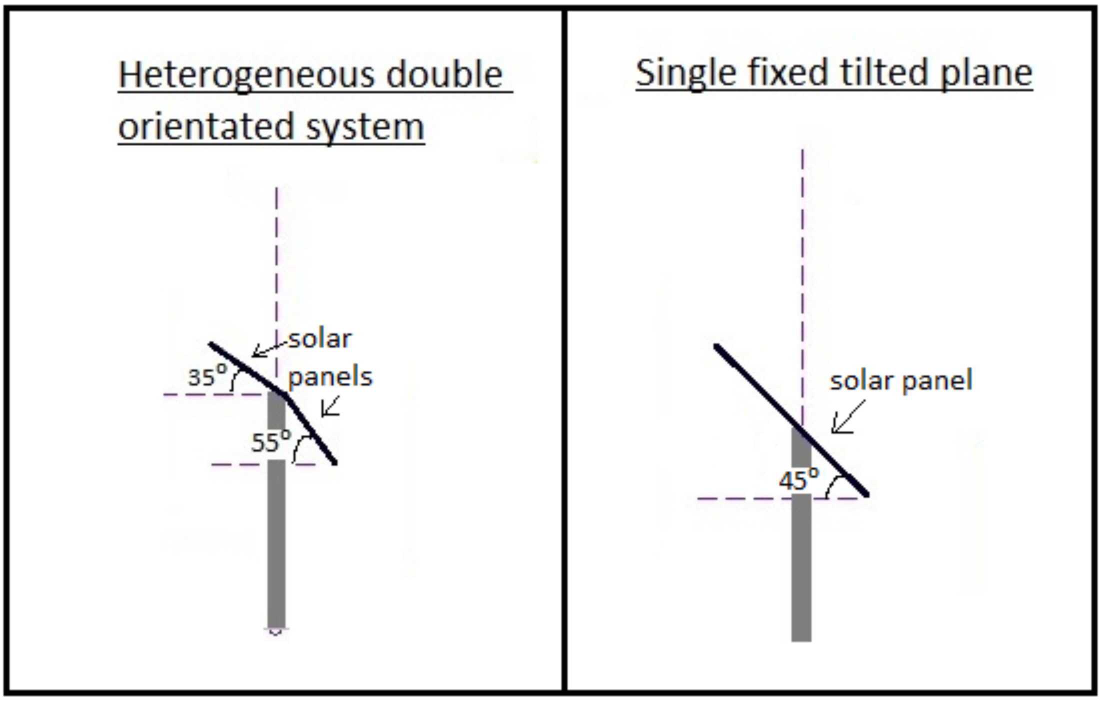

Figure 2: Different tilts.

The difference in system production was approximately 1-2 %, as shown in report "X12 – Placement of Modules", and therefore the heterogeneous double orientated system was chosen because of esthetic reasons. A solar panel with two angles looks smaller and more proper than a large panel with just one tilt angle as shown in Figure 2. It is possible to construct the PV arrays with more angles, but a double system was used in this report, due to limitations in PVsyst. For station roofs, solar racks with 40% ground cover ratio (GCR) and 30° tilt were chosen.

Choice of Components

Modules

Solar cells from Yingli Solar of type 27V Si-poly YL250P-32b with 250 Watt-peak (2009) was chosen for the system. Vattenfall, one of Europe's largest electricity producers, install modules from Yingli of a similar type with 270 Wp and the measurements 1970x990 mm, for private customers. However, for this project, slightly smaller solar cells from Yingli with measurements 1810 x 990 mm were chosen to fit selected panel dimensions. The width of each panel in the heterogeneous system is 3650 mm and therefore two modules with the width 1810 mm will be placed in the panel as shown in Figure 3.

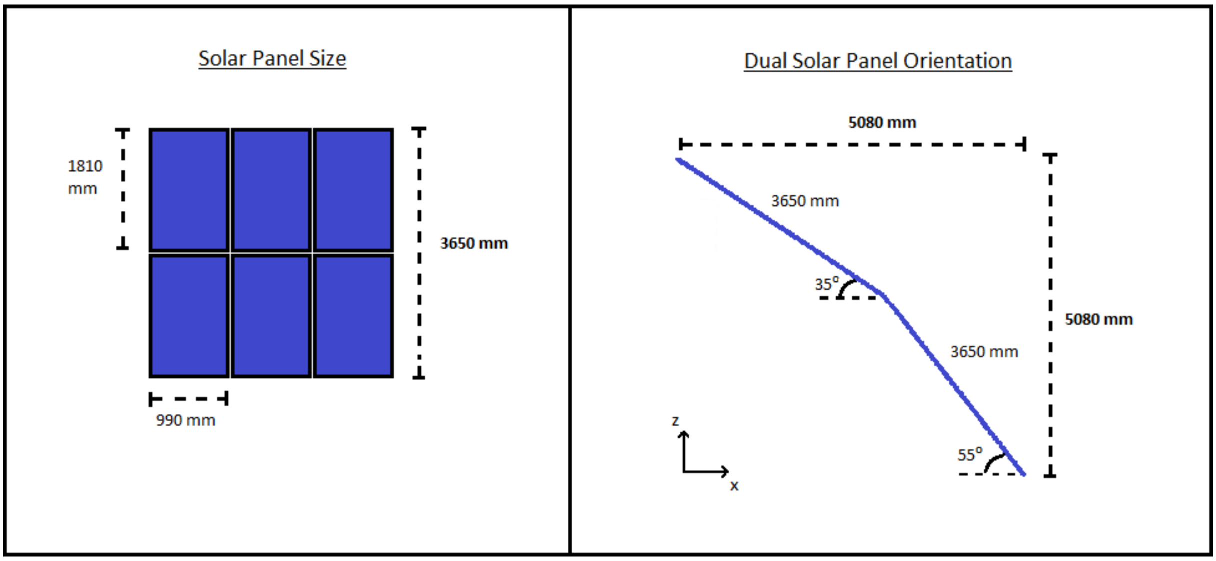

Figure 3: Dimension of the PV arrays.

Converter

The track is supported by a sturdy pillar every 30 meters which will be the placement choice for the inverters. For the simulations the mainly used inverter type were Sunny Tripower 9000 TL-20, an 9 kW inverter from SMA Solar Technology, which is a popular brand for PV installments in Sweden. This type of inverter has a EURO efficiency of 97,6% which is within the standard range for present converters available on the market. For the simulations, the choice of inverter is not critical for the result in overall system efficiency. In some cases different inverters where used, to keep the overload losses within the acceptable limits defined in PVsyst, and the total inverter losses below 3,3 %. For a list over inverter types used in simulations see Table 2 in appendix. PVsyst mimics the behavior of inverters, such as the non-constant efficiency described in report "X21 – Photovoltaics and converters".

Installation

To simplify installations of the heterogeneous PV arrays, they would need to be factory-fitted. A practical dimension of length for the PV sections would be 24 meters (Swenson 2013), and therefore, if the distribution of support-pillars for the track is reoccurring every 24 meters, it would be an ideal choice of placement for the inverters. The proposed length between pillars, for support and safety reasons, is maximum 30 meters. The placement of converters for each 24 meter array will have to be shared on available pillars, which also depends on site-specific conditions.

An array of 24 meter could consist of four series with 24 PV modules, if these have the dimension 1.81 x 0.99 m. If using solar panels of 250 Wp, this would result in the requirement of a 24 kW inverter power for each section. Caution must be taken to not exceed the highest V_{oc} (open circuit voltage) allowed; in Europe this is 1000 V (Brooks et al 2009). A series of 24 PV modules, of the type used in the simulation (Yingli Solar 27V Si-poly YL250P-32b), would not be feasible in this installment, since this would cause the V_{oc} to exceed 1100 V, already at -10 °C. However, the operating voltage will be around 600 V for normal operating conditions and a solution could be to use modules with lower operating voltage and higher current. Due to the heterogeneous placement of the strings, multiple MPP inputs will be required and this can be done by using two SUNNY TRIPOWER 12000TL converters from SMA. These are 12 kW three phase inverters with a rated input voltage of 600 V (max 1000 V), and two separate MPP inputs (SMA no date). By connecting the four strings to separate MPP inputs, these strings could operate at different voltages and the shading of one string would solemnly contribute to its own production losses. Additionally, this would allow for a construction of an array with more angles. By using a high operating voltage, parallel connection of the module is avoided, allowing use of bypass diodes to further minimize shading losses.

Settings in PYsyst

The setting for system losses were kept at default setting in PVsyst with a thermal loss factor of 20 W/m^2K among other setting. Losses due to soiling of the modules were ignored, since these can be considered small, around 1%, for rainy conditions such as in Uppsala. Snow, leaves and bird droppings etc. might have an impact on this loss-factor but it was chosen not to be included in the simulations. Weather data from an average year in Uppsala, received from Meteonorm 5.1, were used in the simulations, along with albedo setting shown in Table 1.

Table 1: Albedo settings used in simulations.

Month	Albedo
Jan	0,7
Feb	0,7
March	0,3
April	0,2
May	0,2
June	0,2
July	0,2
Aug	0,2
Sep	0,2
Okt	0,2
Nov	0,2
Dec	0,3

System Production and Efficiency

The purpose of the project was to have a self-sufficient podcar system and therefore dimensioning was done to reach designated capacity of the system. Two different energy consumptions for the system were determined in report X22 – Travel simulations in Arena, via simulated traffic modeling of the track according to travel patterns and energy data from Beamways. Three different energy production scenarios (A, B and C) were simulated in PVsyst as a comparison to illustrate alternatives when designing the podcar system. The efficiency from inverter output was assumed to be 90 %; hence the production from the modeled PV system exceeds the calculated consumption of the PRT system in report X22. Simulations were done for each productive segment of the system and then summarized to illustrate the total production of the system every hour of the year for each scenario. The most productive parts of each system were chosen in regard to orientation and shading losses. The eleven productive segments of the track are listed and shown in Figure 4 and Table 2.

Table 2: Simulated routs in PVsyst.

Number	Distance [m]	Azimuth [°]	Capacity* [kWp]	Name
1	425	47	430	Railway
2	495	-44	504	Strandbodgatan
3	144	68	147	Östra Ågatan
4	316	-33	320	Studenternas
5	125	-77	126	Akademiska Sjukhuset
6	90	-10	90	Akademiska Sjukhuset
7	80	28	80	Akademiska Sjukhuset
8	240	75	242	Akademiska Sjukhuset
9	60	-10	60	Akademiska Sjukhuset
10	60	50	60	Science Park
11	60	27	60	Science Park
Total	**2095**	**5,4****	**2119**	

*Installed capacity used in Pvsyst-simulations. **Average azimuth.

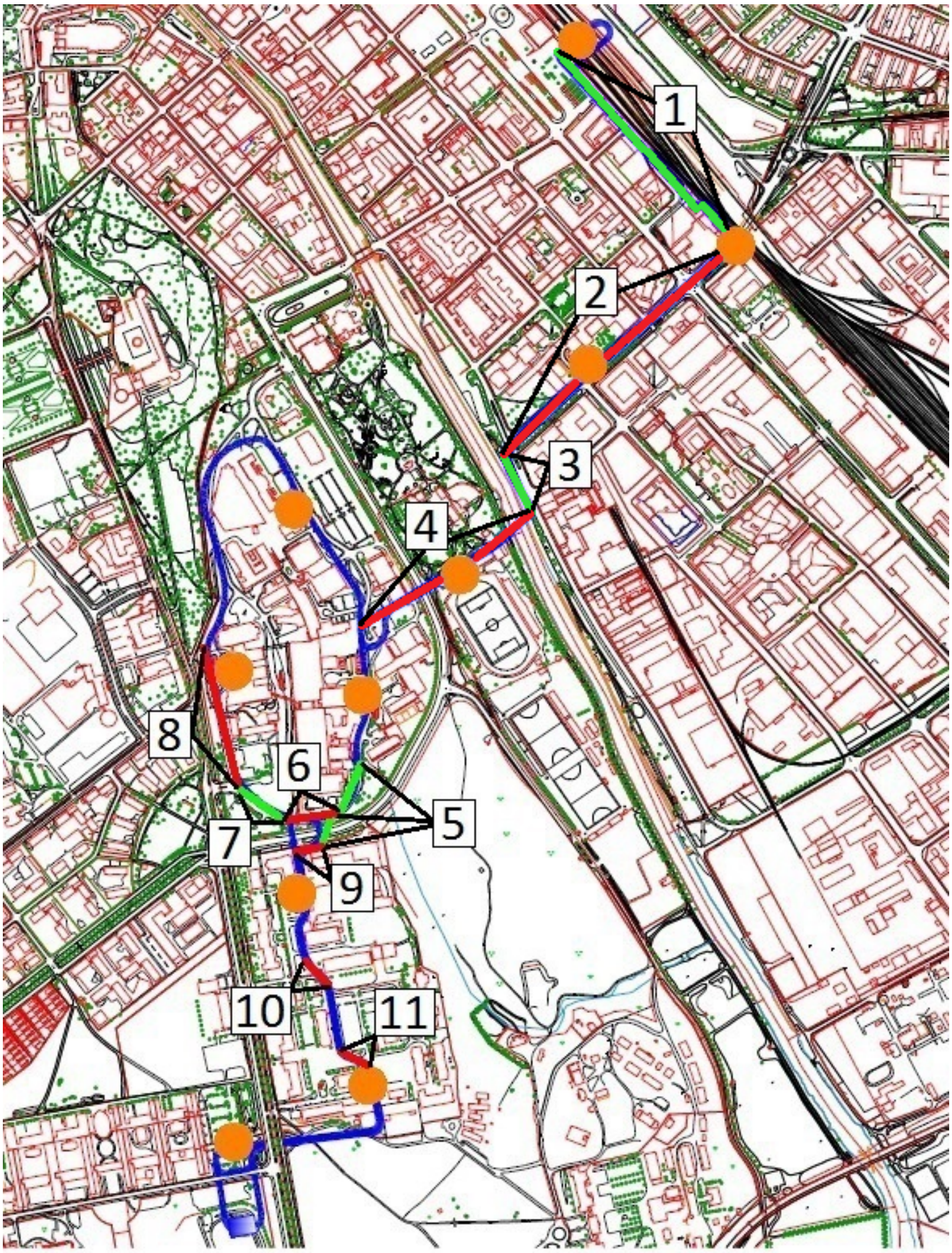

Figure 4: Uppsala podcar track map. (Hunhammar, Lindström 2011b)

Production Scenarios

Scenario A – 1670 kW

In the primary scenario (scenario A), the goal was to cover the annual energy requirements of the PRT system in regard to the standard energy consumption of 1356 MWh each year. All listed segments of the track (excluding part 2, part 5 and half of part 8) and approximately 5450 m^2 of station roof and other areas, were equipped with solar cells with a ground cover ratio (GCR) of 40%. This resulted in a self-sufficient 1670 kW system, resulting in an annual output of 1500 MWh. However, excessive amounts of energy was produced and sold during the high production summer period of March through September while, during the remainder of the year, the system was dependent on grid supplied energy.

Scenario B – 2420 kW

In the secondary scenario (scenario B) with a self-sufficient system, the pod car energy consumption was assumed to be 50 % higher resulting in an annual consumption of 1907 MWh. Therefore, system capacity was expanded to 2420 kW by adding solar cells to remaining parts of the pod car track in order to support new requirements, resulting in an annual output of 2100 MWh. The amounts of solar panels on the station roofs were assumed to be the same as in scenario A. However the system was still dependent on grid supplied energy during the winter half of the year and produces excessive amounts of energy during summer.

Scenario C – 1040 kW

In the third scenario (scenario C), the system was minimized to solemnly support the average energy consumption of 113 MWh during the summer months, this is the average monthly consumption in scenario A. As an alternative to the other scenarios, solar cells were completely removed from all station roofs and the amounts of solar cells along the track were reduced in order to lower the system capacity to 1040 kW. Only parts 1, 4, 6, 9, 7 and 11 of the track were equipped with solar equipment in this scenario. This system produces 930 MWh per year and is extensively dependent on grid-supplied energy in comparison to the other production alternatives.

Energy Supply and Demand

Annual Energy Balance

There are more segments of the track that, at an increased economic cost, theoretically could be equipped with solar cells to marginally increase energy production. However, because of shading and orientation issues, it was discovered that these parts of the system would be of minimal importance to the complete system. Additionally, these low productive segments would be unproductive during the darker months of the year. Since the energy production is seasonally dependent, as opposed to the energy demand, it is therefore not possible to support the energy consumption during the winter half of the year, regardless choice of scenario. The energy production diminishes without sunlight and grid supplied energy will be required to support the system during many days of the year. Annual energy consumption and production has been plotted in Figure 5 and it is obvious that the production is substantially greater during the summer as compared to winter. Regardless which production scenario is chosen, grid supplied energy will be required to support the PRT system during the darker months of the year.

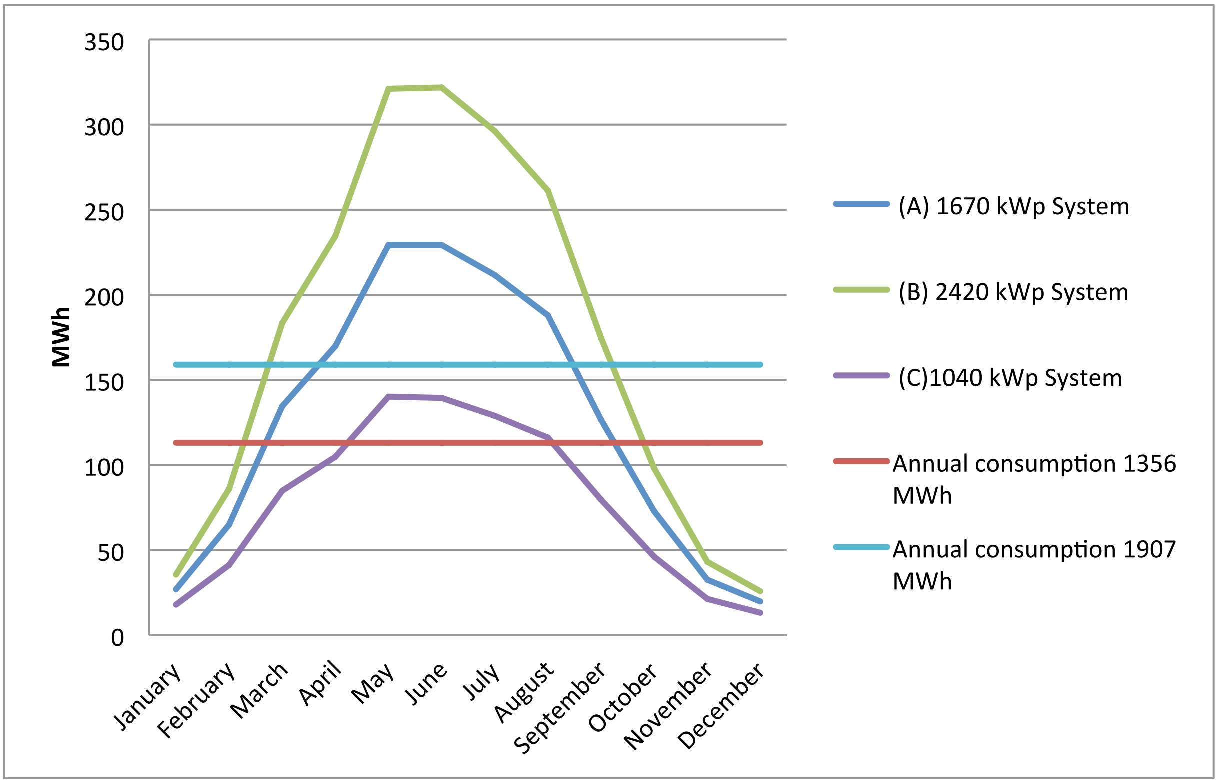

Figure 5. Annual energy supply and demand.

Daily Energy Balance

The average consumption was assumed to be 113 MWh per month according to report "X22 – Travel simulations in Arena", and to illustrate daily variations in energy production and consumption, an average daily production curve was completed for each month of the year and plotted against the standard system consumption for corresponding months. The energy requirements of the PRT system peaks in the morning hours 7 to 9 am and in the afternoons 3 to 5 pm, when people travel to and from work. Since the production peaks between 10 am and 2 pm, batteries could be used as storage in order to reduce the dependency of grid supplied energy, for more information concerning energy storage see report X31 – Energy Storage. Additionally, the PRT system is intended to run every hour of the day and therefore batteries will be required to store energy for night operation.

In the months March – May, the systems in scenario A and B are estimated to be self-sufficient, increasing monthly production and normally, the annual peak-production hour is reached in May. The amount of light hours increase towards the end of this time period and therefore the system becomes decreasingly dependent on grid supplied energy. The battery storage system is of great importance during these months in order to support peak-consumption hours in the mornings which is further explained in report X31 – Energy Storage.

The Summer months of June-August is the most productive season of the year and large amounts of excessive energy is produced during this time period, which can be sold and redistributed back to the into the electricity grid. Storage of energy via the battery system is decreasingly required since production curves match peak consumption since the sun rises earlier and sets later in the day.

Therefore, storage of energy can instead be used predominantly for night operation of the pod car system.

In autumn, September – November, the amount of light hours become subsequently fewer and the pod car system becomes increasingly dependent on grid supplied energy. Again, battery storage is primarily used to support peak-consumption hours in the morning. In November the average watt-peak production is lower than the daily peak consumption resulting in a larger daily purchase of electricity.

Electricity production from the PV system is not reliable during winter months December - February. In February the production and amount of light hours begin increasing again.

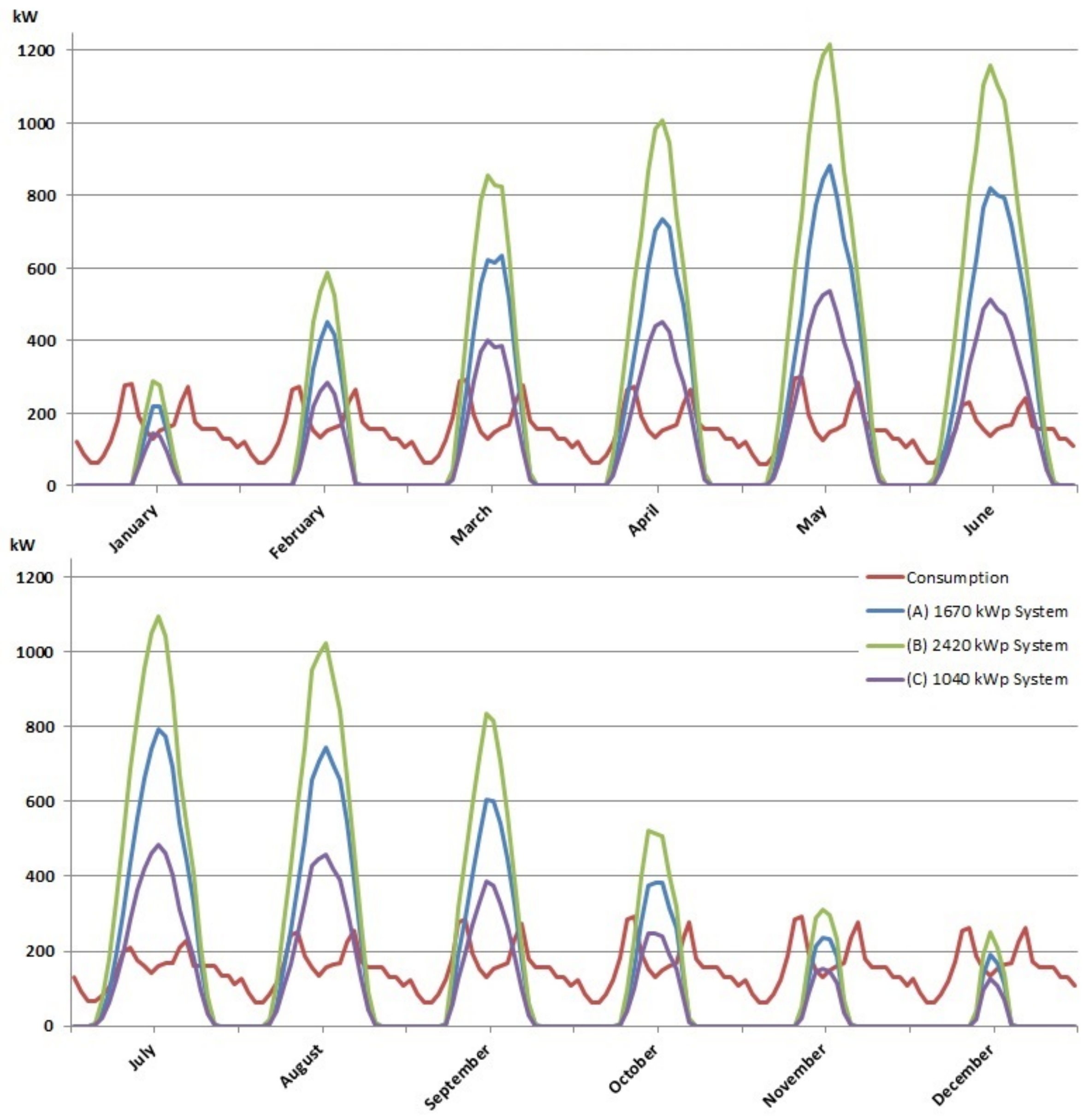

Figure 6: Average daily production for each month, for production cases A, B and C, plotted against the average daily consumption (1,5 GWh/yr scenario) of each month.

Losses

Orientation and Shading Losses

All three scenarios have different shading and orientation losses depending on which segments of the podcar track were chosen. The smaller PV systems have the better and most efficient track sections, minimizing shading and orientation losses. The sheds, which are included in the two larger PV systems, have a capacity of 302 kW and are assumed to be unshaded by neighboring environment, with orientation and internal shading losses amounting to 4% per year. Therefore the total losses, including sheds, is lower with the station roofs included. As a result, the sheds decrease the total losses resulting in the 1670 kW system becoming more efficient than the 1040 kW system, where no sheds we implemented. Figure 7 shows the annual system losses compared to optimal placement of cells which yielded 1041 kWh/kWp each year, for more detailed information see Table 3-5 in appendix. The annual yield computed from the Homer simulation in report "X12 – Placement of Modules" resulted in 953 kWh/kWp. This is the result of different detailed losses and albedo settings in the two simulations. However, since the simulations in PVsyst were run with the same settings, the proportion of orientation and shading losses remains the same regardless of annual yield.

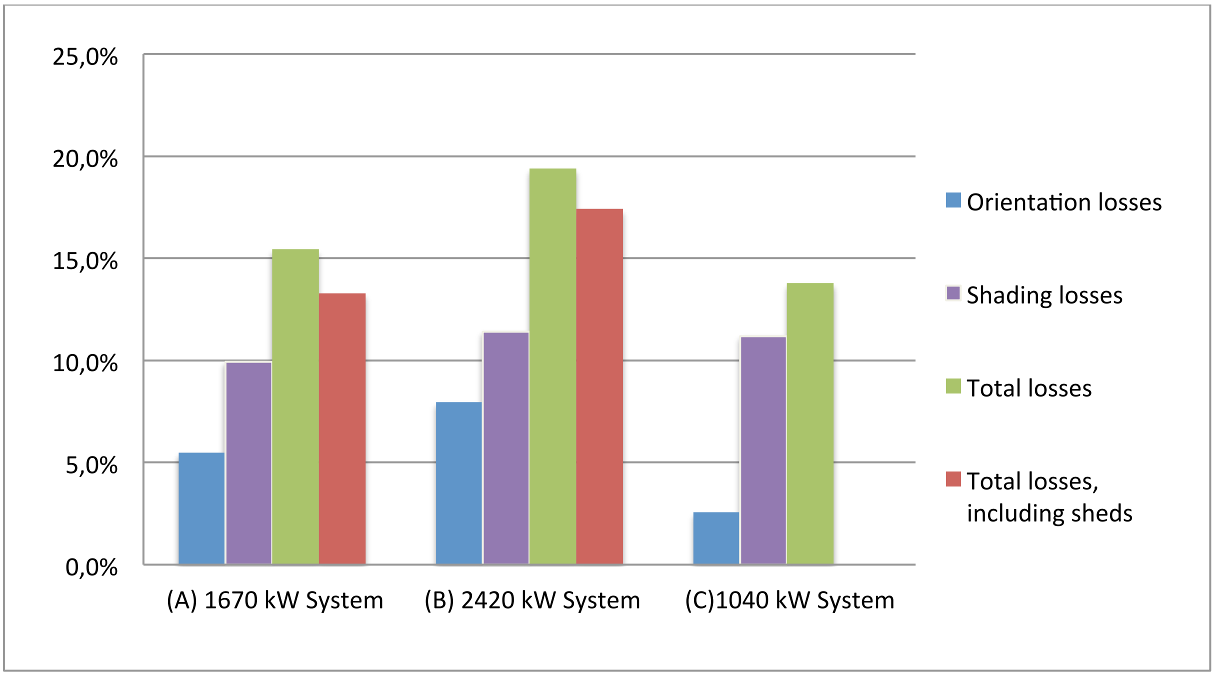

Figure 7: Shading and orientation losses for the three scenarios with respect to annual yield from optimal placing 1041 kWh/kWp. Orientation, Shading and Total losses were calculated excluding the 302 kWp solar sheds installation.

Due to high shading losses, PVmodules on Strandbodgatan were only implemented in Scenario B. Removal of trees on the east side of this street would reduce the losses along this route from 28 % to 22 %, making it as efficient as the sections used in Scenario A.

It is also worth mentioning that shading losses increase during the darker months of the year, since the suns angle of approach is lower, which is displayed in Figure 8. However, since the winter months have a lower electrical production, as can be seen in Figure 5, the shading losses during the months have a lower impact on the annual shading losses displayed in Figure 7.

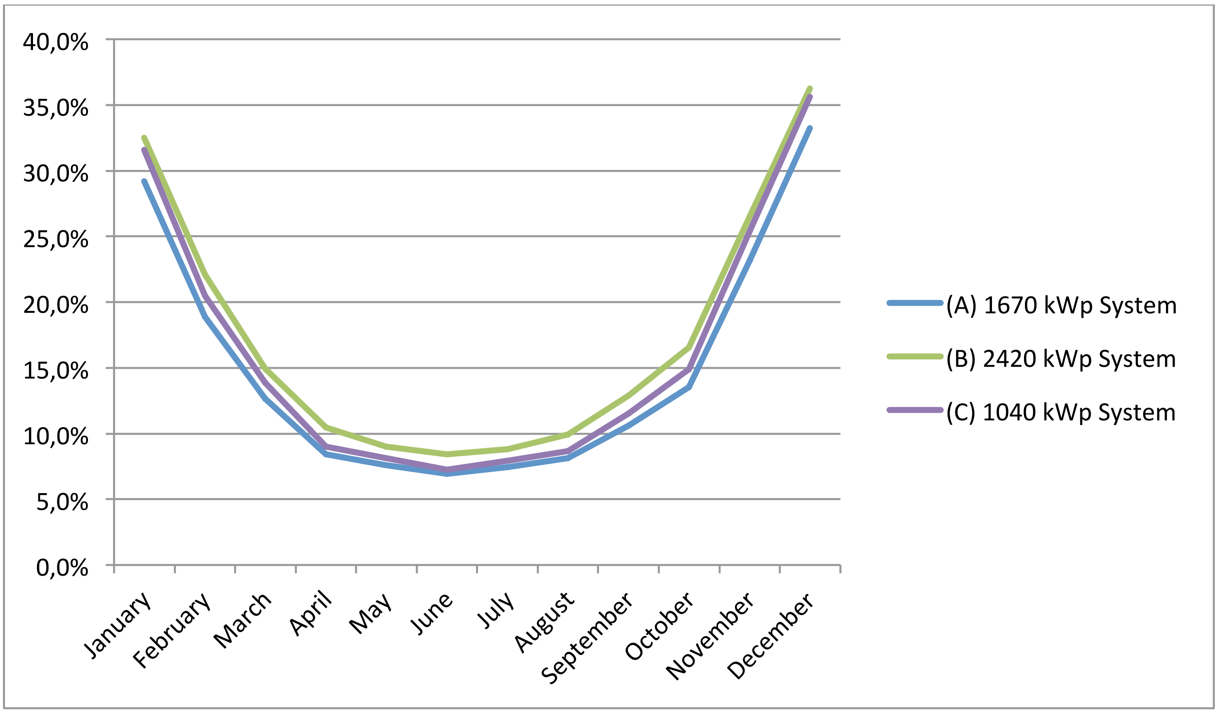

Figure 8: Monthly difference in production between the shaded and unshaded routs. The PV sheds installment of 302 kWp is excluded from the calculations.

Errors

The simulations were run, accounting for linear shading losses. This gives an indication for the minimum shading losses to expect from the system. Depending on how the strings are connected, and how solar maximizes or bypass diodes are integrated in the strings, these losses might get larger. However, the result of the non-linear behavior is not far from the linear case, according to PVsyst, hence the linear estimations where used in the simulations to get an idea over how the system losses would behave.

The models were built using Eniro, Google maps and physical measurements and might differ from reality, but since there are no finished blue prints of the track, it is accurate enough. This gives more of an indication over what the shading losses will amount to rather than the exact value. This will have to be further investigated when the plans for the PRT track's design progresses. In this report the height 7 meters were used for placement to give the podcars a ground clearance of 5,5 meters. Using different placement and heights of the track might result in lower shading losses.

Conclusion

Environment of relevance to the podcar track was constructed in the photovoltaic software program PVsyst. Multiple simulations were completed and summarized for each segment of the track and three different production scenarios were chosen. The most productive areas were primarily chosen and therefore the smaller PV systems have a greater efficiency; hence larger systems having increased orientation and shading losses. Regardless choice of production, energy storage is recommended to support peak-consumption hours. Additionally, grid supplied energy will be needed during the darker months of the year since production is negligible. For the standard scenario with an annual consumption of 1356 MWh, the 1670 kW photovoltaic system is recommended.

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Figures

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Appendix 1 – Additional data

Table 3: Specifications for routs simulated in PVsyst

No.	Name	Distance [m]	Azimuth [°]	Inst. Capacity [kWp]	Nb. of modules*	Converter type	Pnom ratio
1	Railway	425	47	430	1720	Sunny Tripower 9000 TL-20	1,53
2	Strandbodgatan	495	-44	504	2016	Sunny Tripower 9000 TL-20	1,23
3	Östra Ågatan	144	68	147	588	Sunny Tripower 10000 TL	1,45
4	Studenternas	316	-33	320	1280	Sunny Tripower 9000 TL-20	1,39
5	Akademiska Sjukhuset	125	-77	126	504	Sunny Tripower 9000 TL-20	1,17
6	Akademiska Sjukhuset	90	-10	90	360	Sunny Tripower 9000 TL-20	1,39
7	Akademiska Sjukhuset	80	28	80	320	Sunny Tripower 9000 TL-20	1,39
8	Akademiska Sjukhuset	240	75	242	966	Sunny Tripower 17000 TL	1,48
9	Akademiska Sjukhuset	60	-10	60	240	Sunny Tripower 9000 TL-20	1,39
10	Science Park	60	50	60	240	Sunny Tripower 9000 TL-20	1,39
11	Science Park	60	27	60	240	Sunny Tripower 9000 TL-20	1,39

*PV module used in all simulations: Yingli Solar YL250P-32b.

Table 4: Detailed losses for 1670 kWp installment

Shaded rout	**1**	**3**	**4**	**6**	**7**	**8****	**9**	**10**	**11**	***Sheds***	**Total**
Distance [m]	425	144	316	90	80	120	60	60	60	*5449**	1355
Module area [m^2]	3082	1054	2294	657	573	866	438	430	430	*2180*	12003
Installed capacity [kWp]	430	147	320	90	80	121	60	60	60	*302*	1670
Efficiency of array/area	11,12	11,69	11,05	11,53	12	11,46	10,61	10,74	11,12	*11,92*	-
Annual yield from array [MWh/yr]	384	128	295	90	81	99	55	51	57	*312*	1551
Annual yield from inverter [MWh/yr]	373	124	286	87	79	97	53	50	55	*303*	1507
Efficiency of Inverter	0,97	0,97	0,97	0,97	0,97	0,98	0,97	0,97	0,97	*0,97*	0,97
Annual yield [KWh/Wp]	**868**	**844**	**894**	**967**	**987**	**800**	**890**	**831**	**915**	***1004***	**903**
Unshaded rout	**1**	**3**	**4**	**6**	**7**	**8***	**9**	**10**	**11**	***Sheds***	**Total**
Efficiency of array/area	12,07	12,29	12,4	12,36	12,33	6,115	12,36	12,33	12,33	*11,92*	-
Annual yield from array [MWh/yr]	449	134	331	96	83	106	64	59	63	*312*	1696
Annual yield from inverter [MWh/yr]	436	130	321	93	81	103	62	57	61	*303*	1649
Efficiency of Inverter	0,97	0,97	0,97	0,97	0,97	0,98	0,97	0,97	0,97	*0,97*	0,97
Annual yield [KWh/Wp]	**1014**	**888**	**1004**	**1037**	**1014**	**854**	**1037**	**956**	**1016**	***1004***	**987**
Orientation loss	3%	15%	4%	0%	3%	18%	0%	8%	2%	-	-
Shading loss	14%	4%	11%	7%	3%	5%	14%	12%	10%	-	-
Total loss	**17%**	**19%**	**14%**	**7%**	**5%**	**23%**	**15%**	**20%**	**12%**	***4%***	-
Part of installed capacity, excluding solar sheds [kWp/total kWp]	31%	11%	23%	7%	6%	9%	4%	4%	4%	-	100%
Weighted orientation loss	0,8%	1,6%	0,8%	0,0%	0,2%	1,6%	0,0%	0,4%	0,1%	-	5,5%
Weighted shading loss	4,4%	0,4%	2,5%	0,4%	0,2%	0,5%	0,6%	0,5%	0,4%	-	9,9%
Weighted total loss	**5,2%**	**2,0%**	**3,3%**	**0,5%**	**0,3%**	**2,0%**	**0,6%**	**0,9%**	**0,5%**	**-**	**15,4%**
Weighted total loss including sheds	**4,3%**	**1,7%**	**2,7%**	**0,4%**	**0,2%**	**1,7%**	**0,5%**	**0,7%**	**0,4%**	**0,6%**	**13,3%**

*Area covered by solar sheds with a GCR of 40%. **50% of rout 8 where used in this simulation.

Table 5: Detailed losses for 2420 kWp installment

Shaded rout	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Sheds**	**Total**
Distance [m]	425	495	144	316	45+80	90	80	240	60	60	60	*5449**	1970
Module area [m^2]	3082	3612	1054	2294	903	657	573	1731	438	430	430	2180	17384
Installed capacity [kWp]	430	504	147	320	126	90	80	242	60	60	60	302	2421
Efficiency of array/area	11,12	9,68	11,69	11,05	11,47	11,53	12	11,46	10,61	10,74	11,12	11,92	-
Annual yield from array [MWh/yr]	384	392	128	295	101	90	81	198	55	51	57	312	2143
Annual yield from inverter [MWh/yr]	373	380	124	286	98	87	79	194	53	50	55	303	2081
Efficiency of Inverter	0,97	0,97	0,97	0,97	0,97	0,97	0,97	0,98	0,97	0,97	0,97	0,97	0,97
Annual yield [KWh/Wp]	**868**	**753**	**844**	**894**	**775**	**967**	**987**	**800**	**890**	**831**	**915**	**1004**	**860**
Unshaded rout	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Sheds**	**Total**
Efficiency of array/area	12,07	12,07	12,29	12,4	12,26	12,36	12,33	12,23	12,36	12,33	12,33	11,92	-
Annual yield from array [MWh/yr]	449	491	134	331	108	96	83	211	64	59	63	312	2401
Annual yield from inverter [MWh/yr]	436	476	130	321	104	93	81	207	62	57	61	303	2333
Efficiency of Inverter	0,97	0,97	0,97	0,97	0,97	0,97	0,97	0,98	0,97	0,97	0,97	0,97	0,97
Annual yield [KWh/Wp]	**1014**	**945**	**888**	**1004**	**829**	**1037**	**1014**	**854**	**1037**	**956**	**1016**	**1004**	**964**
Orientation loss	3%	9%	15%	4%	20%	0%	3%	18%	0%	8%	2%	0%	-
Shading loss	14%	18%	4%	11%	5%	7%	3%	5%	14%	12%	10%	0%	-
Total loss	**17%**	**28%**	**19%**	**14%**	**26%**	**7%**	**5%**	**23%**	**15%**	**20%**	**12%**	**4%**	-
Part of installed capacity, excluding solar sheds [kWp/total kWp]	20%	24%	7%	15%	6%	4%	4%	11%	3%	3%	3%	-	100%
Weighted orientation loss	0,5%	2,2%	1,0%	0,5%	1,2%	0,0%	0,1%	2,1%	0,0%	0,2%	0,1%	-	8,0%
Weighted shading loss	2,8%	4,4%	0,3%	1,6%	0,3%	0,3%	0,1%	0,6%	0,4%	0,3%	0,3%	-	11,4%
Weighted total loss	**3,4%**	**6,6%**	**1,3%**	**2,1%**	**1,5%**	**0,3%**	**0,2%**	**2,6%**	**0,4%**	**0,6%**	**0,3%**	-	**19,4%**
Weighted total loss including sheds	**3,0%**	**5,8%**	**1,1%**	**1,9%**	**1,3%**	**0,3%**	**0,2%**	**2,3%**	**0,4%**	**0,5%**	**0,3%**	**0,4%**	**17,4%**

*Area covered by solar sheds with a GCR of 40%.

Table 6: Detailed losses for 1040 kWp installment

Shaded rout	**1**	**4**	**6**	**7**	**9**	**11**	**Total**
Distance [m]	425	316	90	80	60	60	1031
Module area [m^2]	3082	2294	657	573	438	430	7474
Installed capacity [kWp]	430	320	90	80	60	60	1040
Efficiency of array/area	11,12	11,05	11,53	12	10,61	11,12	-
Annual yield from array [MWh/yr]	384	295	90	81	55	57	961
Annual yield from inverter [MWh/yr]	373	286	87	79	53	55	933
Efficiency of Inverter	0,97	0,97	0,97	0,97	0,97	0,97	0,97
Annual yield [KWh/Wp]	**868**	**894**	**967**	**987**	**890**	**915**	**898**
Unshaded rout	**1**	**4**	**6**	**7**	**9**	**11**	**Total**
Efficiency of array/area	12,07	12,4	12,36	12,33	12,36	12,33	-
Annual yield from array [MWh/yr]	449	331	96	83	64	63	1086
Annual yield from inverter [MWh/yr]	436	321	93	81	62	61	1055
Efficiency of Inverter	0,97	0,97	0,97	0,97	0,97	0,97	0,97
Annual yield [KWh/Wp]	**1014**	**1004**	**1037**	**1014**	**1037**	**1016**	**1014**
Orientation loss	3%	4%	0%	3%	0%	2%	-
Shading loss	14%	11%	7%	3%	14%	10%	-
Total loss	**17%**	**14%**	**7%**	**5%**	**15%**	**12%**	**-**
Part of installed capacity [kWp/total kWp]	41%	31%	9%	8%	6%	6%	100%
Weighted orientation loss	1,1%	1,1%	0,0%	0,2%	0,0%	0,1%	2,6%
Weighted shading loss	5,8%	3,2%	0,6%	0,2%	0,8%	0,6%	11,2%
Weighted total loss	**6,9%**	**4,3%**	**0,6%**	**0,4%**	**0,8%**	**0,7%**	**13,8%**

Report X31

[Energy Storage]

Authors: Joakim Björk, Christian Jansson, Hanna Jansson

2013-05-28

In order to increase the quality of the power output, decrease impact on the grid and optimize the purchase of electricity, energy storage can be used. In this report, energy storage by batteries is investigated.

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Background

As a distributer of electricity via the city grid, electricity utility based on what power output the grid is burdened by must be paid for. A photovoltaic system is an intermittent energy source and it is impossible to pre-calculate the exact power output generated by the modules. By using in-house energy storage it is possible to ease high power output to the city grid and thereby reduce the costs.

Energy and Power Storage

There is a contradiction between energy and power storage. A certain storage unit is either good at storing energy or power. Batteries, for example, may be used to store energy over a long time, but are unable to provide high power when drained. On the other hand, a flywheel can provide high power output, but has a more limited capacity to store energy over longer time periods.

Some of the benefits provided by energy storage are to utilize more self-generated electricity and increase the power output from intermittent sources. Energy storage can also reduce the power peaks otherwise affecting the grid, which may lead to a reduction in fees from the company owning the city grid. Presently, the most proven method for energy storage is the use of batteries in a system. Therefore, energy storage by batteries is also the method most appropriate for the current need (Abrahamsson 2013, Krohn 2013). When the system produces more than needed, storage of energy commences, and when consumption is higher than production, power is supplied from the storage source. One of the drawbacks of a storage system is that it is expensive, and when possible, it is often more convenient to connect the system to the grid and balance production/consumption through purchase and selling of electricity. (Elforsk 2012a) Furthermore, to connect a power source with the grid, certain conditions set by the grid company must be met. See report X32 - Electrical grid requirements for more details on connecting to the grid.

Consumption peaks are concentrated at 7-9 am and 3-5 pm for weekdays and therefore it is convenient to store energy from peak-production hours at midday for peak-consumption time periods. During night-time, electricity prices are lower. Therefore, direct purchase of grid supplied power for night operation and use of stored power at morning rush hour, when purchase prices are higher, is advisable. In a comparison, four different energy storage scenarios have been investigated. In the first scenario, the energy storage system has a capacity of approximately 0,8 MWh stored energy. In the second scenario, the energy storage has been set to 2 MWh. In the third and fourth scenarios, the energy storages have been set to 4 and 10 MWh.

A battery storage at a size that enables the system to be self-sufficient, i.e. that can store enough energy to power the system when the photovoltaics are not producing, will be too expensive and not of interest for the system in Uppsala. It can, on the other hand, be interesting for countries with other conditions and needs. The electricity grid in Sweden is well functional and, due to access to waterpower, able to manage connecting such a system. A larger energy storage could even the production and consumption peaks and thereby enable usage in areas without these advantages. In locations closer to the equator, with more evenly distributed access to sunlight throughout the year, a storage that enables the system to be off grid could be of interest, due to assumed instability in the grid. Storage sizes to be considered would vary depending on size of the system and conditions on site, but with primary purpose to store enough energy to supply the system for one or more complete days, in order to secure operation even at days with low sunlight access.

Smart Battery Simulations

To simulate a smart battery for energy storage, the calculation software MatLab was used. The code was built from a small battery simulation code, constructed by Joakim Widén. The storage enables the system to use some of the produced electricity at later hours; this will lower the need of selling and buying electricity to the grid and therefore lower the electricity costs. Secondly a control system was designed to ensure that the battery would be sufficiently charged to be able to ensure that the grid purchases during peak loads will not exceed 220 kW power during weekdays, and 180 kW during vacation days. During periods of low solar insolation, the battery can be regulated to buy electricity before the two daily peaks in order to ensure that the grid purchases do not exceed 240 kW, and to lower costs since electricity is more expensive during peak consumption hours. This simulated battery has an efficiency of 90%, which is in between Li-ion (≈100%) and lead-acid (≈75%).

Results

PCS100 ESS

ABB has a complete solution regarding battery storage for sale. The solution is called PCS100 ESS and comes in load capacities ranging from 100 kVA to 10 MVA and provides grid stabilization, power system load levelling, grid compliance for renewable energy sources and power quality improvement (ABB, 2013). The price for installation of PCS100 ESS has not been found. However, a research organization representing Swedish energy companies, Elforsk, has published a report considering initial costs of different sized battery storage systems linked to a wind farm project (Elforsk, 2012b). Data from this report has been used as a foundation in economics calculations for an energy storage system of type PCS100 ESS, since it is plausible that such a system will be utilized.

Initial Costs for Battery Storage

Today, the cheapest battery type for large-scale energy storage is the lead-acid battery. With cost of approximately 50-150 Eur/kWh compared to the more expensive Li-ion 700-1000 Eur/kWh (Divya & Østergaard 2009). At the moment of this report, the battery technology is improving rapidly. Prices are going down and new technologies are being implemented. It is therefore unwise to decide what battery type should be used even a few years from now. The best choice for a battery energy storage at the moment is probably to start with a lead-acid battery and after its first lifetime decide what technology to continue with. By then Li-ion batteries could have gotten cheaper. There is also a possibility of used electrical car batteries, with too low energy density for cars, working together as relatively cheap big scale energy storage. (Mail conversation with Anti Liivat, see Appendix 1)

Table 1: Estimated prices for energy storages containing lead-acid batteries.

Lead-acid	Size of storage [MWh]				
Cost [kSEK]	0	0,8	2	4	10
Investment (low/high cost)	0	344 / 1031	859 / 2577	1718 / 5154	4295 / 12885
Annual, grid connection	225	187	182*	174*	152
Annual, Electricity (Vattenfall/Telge)	216 / 133	186 / 121	146 / 99	126 / 89	117 / 84
Straight Payback time (Low investment cost, Vattenfall/telge) [yr]	-	5 / 7	8 / 11	12 / 18	25 / 35
Straight Payback time (High investment cost, Vattenfall/telge) [yr]	-	15 / 21	23 / 33	37 / 54	75 / 106

*Linear extrapolation

Lifespan: 1000-2000 cycles, higher maintenance

Table 2: Estimated prices for energy storages containing li-ion batteries

Li-ion	Size of storage [MWh]				
Cost [kSEK]	0	0,8	2	4	10
Investment (low/high cost)	0	4810 / 6872	12026 / 17180	24052 / 34360	60130 / 85900
Annual, grid connection	225	187	182*	174*	152
Annual, Electricity (Vattenfall/Telge)	216/133	186 /121	146 / 99	126 / 89	117 / 84
Straight Payback time (Low investment cost, Vattenfall/telge) [yr]	-	71 / 96	106 / 156	171 / 253	350 / 493
Straight Payback time (High investment cost, Vattenfall/telge) [yr]	-	101 / 137	152 / 223	244 / 362	499 / 704

*Linear extrapolation

Lifespan: 3000 cycles

As seen in the Table 1 & 2 above, the payback time for lead-acid batteries are shorter than the payback time for Li-ion batteries. The prices are estimated and the two different investment costs are the highest and the lowest in the interval mentioned for the different battery types. These cost do not consider maintenance and other system costs.

Energy Storage Size Impact on Electricity Sales and Purchases

All the energy storages were able to reduce the consumption peaks to 240kW power, instead of 365 kW, which was the highest hourly peak load without energy storage. This would mean that the cost of grid connections would be lowered. It should be mentioned that the values in Figure 1 below are monthly average numbers and though that it looks like the 10 MWh battery would make the system self-sufficient during most of the summer months, there are hourly negative values that do not show in those graphs.

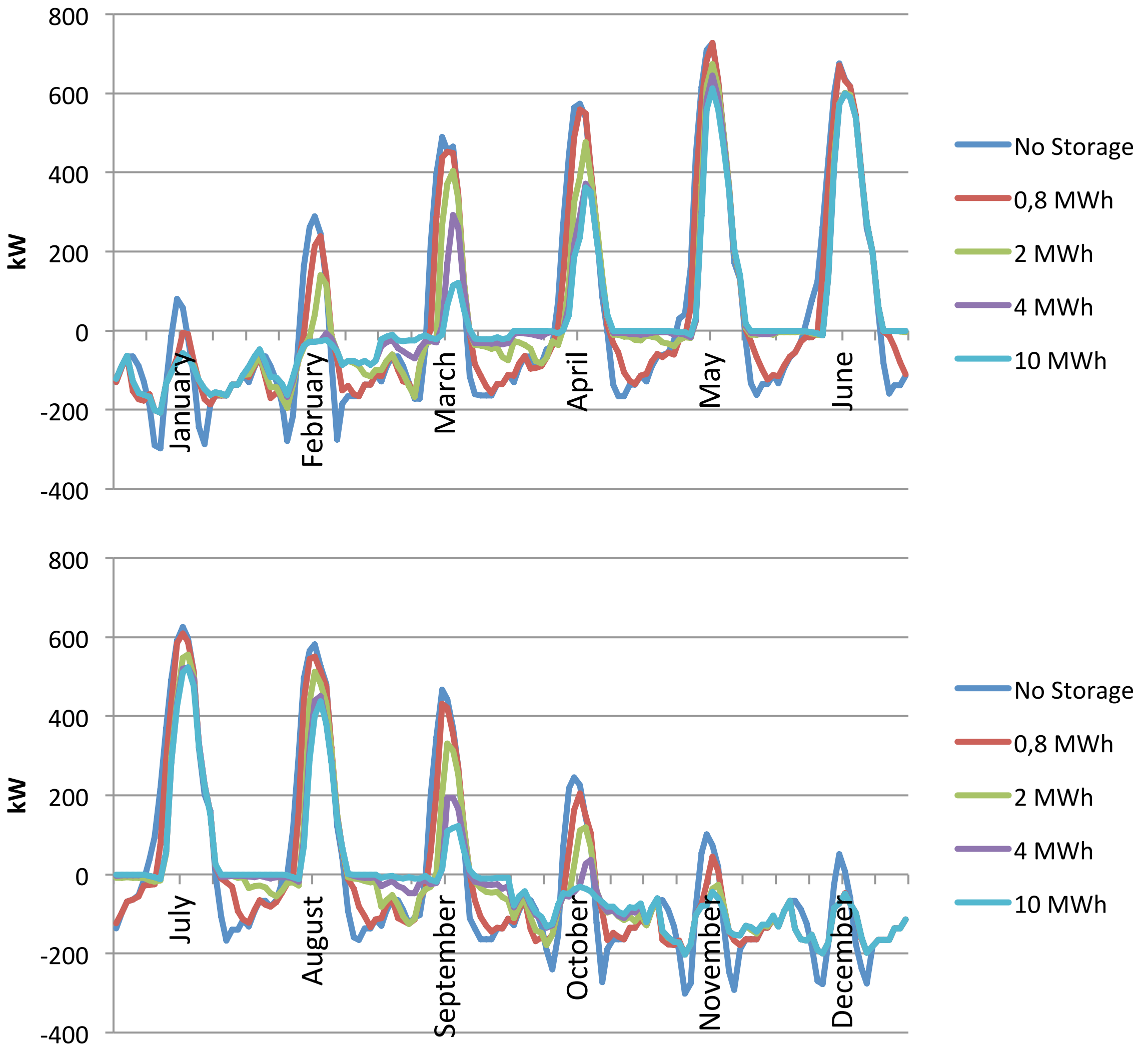

Figure 1: Grid deliveries for different sizes of energy storage during a typical day of the month, for a whole year. Positive values means sales, negative values means buys.

As seen in table 3 below, the need of using the grid as storage is still needed even when using storage of 10 MWh size. The need of using the grid as storage is not decreasing as fast as the battery size increases. This is due to Sweden's great insolation during summertime and weak insolation during wintertime and results in a conclusion that a solar driven system, not relying on the electrical grid, is not economically possible in Sweden.

Table 3: Total yearly sales and buys for Scenario 1 with different sizes of energy storage.

	No storage	0,8MWh	2MWh	4MWh	10MWh
Yearly buys [MWh]	1 428 357	633 254	483 008	406 335	373 919
Yearly sales [MWh]	1 507 167	767 716	587 600	495 233	454 711

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Appendix 1 – Mail Conversation with A. Liivat 2013-05-24

Hej Hanna,

Det ser ut som ett jättespännande projekt och först vill jag önska lycka till med allt detta.

Vad som gäller batterier för tillfälligt lagring av solenergin och jämna dem svängningar för att koppla till elnätet då blir det ett kompromiss mellan lägre kostnader (bly, NiMH) och bättre livsländ (Li-jon). Man kan hitta många jämförelser på nätet, tex http://www.electricitystorage.org/technology/storage_technologies/cost_considerations: det ser ut att 1MWh kostar ungefär 5MSEK för bly och dubbelt så mycket för Li-jon. Rapporten från Elforsk verkar ge ungefär samma siffor. Problemet ära att just nu är det kanska svårt att välja särskild batteriteknologi för tillämpningar som kräver båda stora volumer (MWh) och livslängden över 5 år. Det är därför att batteriteknologier för sådana tillämpningar forskas och utveklas just nu jättemycket och därför är det svårt att räkna vad det blir för kostnaderna inom ett par eller 10 år. En möjlighet är att räkna med billigaste teknologin just nu (bly-kol eller NiMH) om projektet ska vara på gång inom 2-3 år, och reservera för upgradering av hela lagringsystemet (till Li-jon eller Na-jon) ca 3-5 år senare för ett system med längre, >10-20 år livslängd. Då blir det också ett möjlighet att använda så kallad "second-hand" fordonbatterier - batterier som har används redan ca 5år i elbilar och har tappat ~20 % kapacitetet, men kan fungera utmärkt som stationärt largringsystemet för utterligare 5-10 år (se Cairns, bifogad).
Jag tror det går också att kontakta företag i Sverige som Electroengine, ETC, LiFeSize för utterligare detaljer om Li-cell kostnaderna.

Jag bifogade också ett par artiklar som kanske kan hjälpa till.

Hälsningar,

Anti Liivat
Forskare
Kemi Ångström
Uppsala Universitet

SOLAR SKYWAYS

Report X32

[Electrical Grid Requirements]

Authors: Björn Isaksson, Erik Lindholm

2013-05-28

Requirements, limitations and conditions to be met, when designing grid connections to the planned PV system, have been investigated and analysed in this report. Results indicate that the connection cost will be approximately 225 000 SEK per year for the standard scenario; whereas the annual system consumption is 1356 MWh and production 1670 MWh. However, for specific circumstances, it is possible to reduce connection costs by lowering peak-values with an energy storage system and regulation techniques.

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Method

Background

There are two main conditions to be met when designing connections to the grid regarding the energy production of the PV system and energy consumption of the PRT system. The first objective is to assure that the system meets the requirements of the electricity grid and the second is to optimize the energy storage to meet the net production/consumption and decrease electricity purchases. The question regarding meeting the electrical grid requirements will be discussed in this report and optimization of energy storage is discussed in report X41.

The owner of Uppsala City electrical grid, Vattenfall AB, is legally bounded to connect both the energy input and output from the system. In cases like this one, it is the customer's responsibility to pay for grid reinforcements that may be required to increase the grids capacity. Therefore, the aim of this study is to dimension connections to and from the PRT system in order to meet the installed grid capacity.

Grid Requirements

Within the frame of regulations, it is required that energy transmission to and from the system in no single connection point may exceed the following requirements:

- Energy consumption must not result in voltage- and/or power fluctuations over three per cent of the electrical grids standards. These values must be managed even if the system is fully rebooted.
- Any single load must not result in voltage- and/or power fluctuations over one per cent of the electrical grids standards.
- The electricity production must not result in voltage- and/or power fluctuations over five per cent of the electrical grids standards. These values must be managed even if the production is fully rebooted.

Other requirements concern reactive power, flicker and overtones. Reactive power should not be of any concern since the podcars DC motors do not consume it. Neither should flicker be of any concern since voltage fluctuations are not likely to be too rapid. Harmonics (overtones) may be of concern due to the many rectifiers, inverters and other power electronics. In the case of construction of the PRT system, this problem will have to be investigated. Overtones are not considered in this report (Söderberg, 2013).

System Design

After discussions with David Söderberg, consultant at Vattenfall Power Consultant AB, the following system design, as mentioned in Report X21, was chosen:

- The DC podcar system, 750 V & <370kW will be connected to the middle voltage grid (11-20 kV, 50-300 MVA). Rectifiers and transformers will be needed.
- The systems AC consumption: lighting, computers etc. will be connected to the low voltage grid (0,4 kV).
- The solar electricity production will be connected to the low voltage grid.

Electricity Prices

To get an overview of the economic situation for the system, dialogues with both grid- and electricity companies have taken place. Since the system is not there now, it is very difficult to predict the precise prices for purchasing and selling electricity. The prices may also vary depending on what agreement is arranged with the company in question. Vattenfall have been contacted as they are the owner of the low and medium voltage grid that the PRT system will be connected to. Telge Energi is an electricity utility with experience of solar produced electricity and has also been contacted. The difference between their prices are extensive, but as seen in Table 1, the quota is similar; i.e. ~0.50 SEK/kWh excluding certificates (Söderberg 2013; Sundelius 2013). In calculations, prices from Vattenfall will be used, since collaboration with them is further developed and therefore more plausible.

Electricity Certificates

In May 2003 the Swedish government introduced a law for electricity certificates, with the objective to increase the portion of renewable electricity production. The goal is to increase the yearly renewable electricity production by 25 TWh, from 2002 to 2020. In cooperation with Norway, the goal is to increase this by an additional 13,2 TWh, between 2012 and 2020. (Energimyndigheten 2012a) The system assigns certificates for each MWh of renewable electricity delivered by the producer. The producer is then able to sell the certificates on the market. Buyers are operators with so-called quota obligations; these are primarily the electricity suppliers. The amount of certificates needed is regulated by a quota, set by the "Law of electricity certificates". 2013 this quota was set to 13,5% and increases to 19,5% in 2020. After 2020 the quota declines to 0,8% by 2035. New plants are entitled to certificates for 15 years until 2035. (Energimyndigheten 2012b) In 2012-2013 the price for certificates has varied between 0,14 and 0,25 SEK/kWh. (Modity 2013) The price is set by supply and demand and will most likely drop in the future with the expansion of renewable electricity production and lowering of the quota after 2020.

Table 1. Rough estimate of prices for purchases and sales of electricity and electricity certificates. In the Telge Energi case, the electricity is specifically solar produced.

Company	Sells for [SEK/kWh]	Buys for [SEK/kWh]	Electricity certificate
Vattenfall	0,75	0,25	0,2
Telge (solar power)	1,8	1,3	0,2

Cost of Grid Connections

Electricity Consumption

Important parameters to take into consideration when calculating the costs of grid connection are:

- Fixed connection cost (Table 2, Fixed).
- Highest hourly average power outtake per month (Monthly power) and extra cost for consumption in the months January, February, March, November and December (Peak load time).

- Consumed energy during the weekdays between 06 am – 10 pm in the months January, February, March, November and December (Transmission, peak load time).
- Consumed energy during remaining months of the year (Transmission, other time).

(Vattenfall 2012)

Electricity Production

As a producer of electricity, the costs and compensations vary depending on the scale of energy production of the system. A small-scale producer is a facility with a production within the gap 43.5 to 1500 kW (Vattenfall 2013a). As a small scale producer, the only cost of being connected to the grid is a measurement fee, which lapses if you simultaneously consume electricity via the same connection, resulting in generation of compensation for produced electricity. Therefore, the production in Scenario A, as described in report X23 – Dimensioning the Photovoltaic System, was dimensioned to never exceed 1500 kW.

Parameters to consider when calculating the compensations of grid connection are:

- Produced energy during the weekdays between 06 am – 10 pm in the months January, February, March, November and December (Table 3, Transmission, peak load time & Energy compensation, peak load time)
- Produced energy during remaining months of the year (Transmission, other time & Energy compensation).

(Vattenfall 2013b)

Results

Costs of Grid Connection

Table 2 and 3 show the grid connection costs for the standard scenario (1) where the system consumption was 1356 MWh per year and annual production was 1670 MWh.

Table 2. Power tariff for buying electricity, in the case of no energy storage.

Power tariff, buy	Month													
Type of cost	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Okt	Nov	Dec	Tot	Pot
Fixed	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	21600	0,081
Monthly power[1]	7677	7677	7651	6954	6911	3965	4949	5808	7541	7653	7677	7677	82141	0,306
Peak load time[2]	16506	16506	16450	0	0	0	0	0	0	0	16506	16506	82475	0,308
Transmission, peak load time[3]	12668	9024	6992	0	0	0	0	0	0	0	11862	12661	53207	0,198
Transmission, remaining time[4]	1849	1471	1867	2813	2258	1810	2199	2559	3531	4884	1575	1860	28676	0,107
Total	40501	36479	34760	11567	10969	7574	8948	10167	12872	14337	39420	40504	268099	1
Part of total (Pot)	0,151	0,136	0,130	0,043	0,041	0,028	0,033	0,038	0,048	0,053	0,147	0,151	1	

Table 3. Power tariff for selling electricity, in the case of no energy storage.

Power tariff, sell	Month													
Type of cost	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Okt	Nov	Dec	Tot	Po
Energy compensation, peak load time[5]	-666,3	-2018,6	-4655,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-804,3	-361,5	-8506,0	0,2
Energy compensation[6]	0,0	0,0	0,0	-4638,3	-6607,9	-6726,6	-6186,9	-5218,6	-3302,0	-1717,4	0,0	0,0	-34397,8	0,8
Total	-666,3	-2018,6	-4655,3	-4638,3	-6607,9	-6726,6	-6186,9	-5218,6	-3302,0	-1717,4	-804,3	-361,5	-42903,7	1
Part of total (Pot)	0,02	0,05	0,11	0,11	0,15	0,16	0,14	0,12	0,08	0,04	0,02	0,01	1,0	

1. Determined by the highest hourly average power outtake per month.
2. Extra charge for the highest hourly average power outtake during January, February, March, November & December.
3. Determined by total energy transmitted between 06-22 during January, February, March, November & December.
4. Determined by total energy transmitted between 22-06 during January, February, March, November & December and all times during April-October.
5. Determined by total energy transmitted between 06-22 during January, February, March, November & December.
6. Determined by total energy transmitted during April-October.

As illustrated in Table 2 and 3, the total costs for connecting the systems to the grid, in regard to consumption and production, is 225 195 SEK per year. Naturally, consumption generates cost, while the production provides income. If, however, the production is to increase to over 1500 kW, which is the situation in the high energy production scenario, the facility will be classified as a large-scale production facility and additional costs of production, similar to the consumption costs, will apply. If the system is built, it will be necessary to connect to the grid via multiple connection points in order to secure the systems supply and demand of energy. This will increase the costs by 21 600 SEK per connection and year for the consumption, and 2 400 SEK per connection and year for the production.

Energy storage would result in a reduction of grid connection costs. Results from calculations have shown that connection costs of 225 195 SEK can be lowered to 186 774 SEK with 0.8 MWh storage and to 151 750 SEK with 10 MWh storage.

Ways of Decreasing Grid Connection Costs

The main cost of connecting the system to the grid is the charge for the highest hourly power outtake, especially during the months January, February, March, November and December. A clever battery storage system, which could smoothen out consumption curves, would be able to reduce peak values and thereby lower the connection costs. However, battery storage is very expensive and would, despite lowering grid connection rates, have difficulties bearing these increased costs. If a storage system was installed for other reasons, such as storing the solar electricity for sunless hours, a clever control system would be able to lower the costs as a bonus.

Management of Grid Limitations

The grid owner, Vattenfall, is certain that connecting a system of this size, with production and consumption in the scale of some hundred kilowatts per connection point, should not be a problem, since the Uppsala city grid is strong, as mentioned by P-O. Nilsson via email (see Appendix 1). The system itself will, most certainly, require several connections to the grid to reduce the internal losses. This would at the same time lower the strain on the grid. Finally, in occurrence of a system shut down, each podcar's internal batteries should be sufficient to transport them to their final destinations, or in worst case, to the nearest station. At start up, the internal batteries could be used to lower start up peak-buys. It is also possible to activate and restart the podcars gradually for the same reason. When the PV system is to be built, it is the grid owner's responsibility to assign a specialist group with the task of acquiring detailed results concerning grid capacity; is it sufficient or will it need reinforcement? This cost will later be placed on the customer.

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Appendix 1 – Mail from P-O. Nilsson 2013-05-23

per-olof.nilsson@vattenfall.com

Hej !

Hur många anslutningspunkter det ska vara på högspänning för förbrukningen respektive på lågspäning för elproduktionen beror på hur behovet i verksamheten ser ut. För att spårtaxin ska fungera tekniskt krävs troligen en anslutningspunkt för en viss längd och ju längre bana desto fler anslutningspunkter. Likaså måste inmatningen till elnätet anpassas till var solcellerna i praktiken blir placerade. Blir det på ett ställe blir det en enda stor anslutningspunkt och är det mer utspritt blir det flera mindre. Elnätet byggs ut flexibelt för verksamhetens behov. Anslutningar upp till några hundra kW är nästan alltid lågspänning och det förekommer upp till 1 MW. Större anslutningar än så är normalt högspänning. Så antalet anslutningar är helt beroende på verksamhetens behov.

Hälsningar

P-O Nilsson

Re:
Vi har nu fått fram både produktion och förbrukning, med och utan reglering med batterilager. Det vi undrar över är om det på något lätt sätt går att förutse hur många anslutningar som skulle behövas till nätet för att nätet ska klara av att tillgodose förbrukningen och ta emot produktionen?

Den maximala entimmeseffekten för förbrukningen är 365 kW, 750V (ansluts till mellanspänningsnätet: 11-20 kV, 50-300MVA). Den maximala entimmeseffekten för produktionen är 1130 kW, 400V (ansluts till lågspänningsnätet: 400V). När det gäller lågspänningsnätet har vi inte lyckats hitta information kring vilken effekt det är dimensionerat för.