European Spallation Source Solar Concept

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Overview

In the summer of 2014, a informal collaboration was formed between Lund Tekniska Högskola (LTH) and the European Spallation Source (ESS) Accelerator Division to study the possibility of using solar energy to partially power the ESS linear accelerator. Our preliminary investigations have revealed that the solar energy potential of ESS site is comparable to many of the large scale solar fields found in Germany and other sites in northern Europe. A larger percentage of the ESS site has the potential to be used as a solar field. Because of the availability of municipal district heating systems in southern Sweden near ESS, ***the capture of thermal heat*** in addition to electrical energy from a solar field ***could bring the efficiency of large scale solar installations to a new level***.

By connecting the ESS linear accelerator power converters to a photovoltaic solar field that occupies about one-third of the ESS site, the field could produce ***electrical power*** at a yearly average operational rate ***exceeding 6 MW***. This is more than enough energy to offset the energy supplied to the ESS proton beam emanating from the world's most powerful linear accelerator. In addition, it might be possible to collect from the solar field a yearly average of 20.7 MW-year of thermal energy at a temperature of 80C. ***This amount of thermal energy is over five times greater than the amount of heat that is planned to be recycled from the ESS Linac***; a cornerstone of the ESS renewable energy policy. Collection of ***thermal energy during the winter months could exceed a daily average of 8.8 MW-day.*** This captured heat energy could then be fed directly into the Lund central heating district providing a significant carbon-neutral source of energy for the city of Lund, Sweden. The yearly sum of electrical and thermal energy from this field would exceed 24 MW-years. Since the estimated yearly energy usage of ESS is expected to be less than 20 MW-years, this solar field could ***produce 20% more energy than ESS consumes***.

Since the ESS project will be built in stages with the ***first stage*** to be capable of providing 1.2 MW of beam power, the solar field could also be built in stages that match ESS construction project. A hybrid solar field that occupies less than 12% of the ESS site could ***provide electrical power*** at a yearly average operational rate ***exceeding 2.1 MW*** which is more than enough ***to compensate for the entire amount of energy supplied to the beam in Stage 1 by a factor of almost 2***. The ***thermal energy available*** from a first stage solar field could exceed 7 MW-years which ***is over six times the amount of heat planned to be recycled from the ESS linac*** in the first stage of the ESS project.

Introduction

ESS is an accelerator-based neutron source facility that will provide the most intense pulsed neutron beams in the world for scientific research and industrial development. ESS is being constructed in Lund, Sweden on the same campus as the MAX IV synchrotron light source. ESS and MAX IV are complementary facilities that along with LTH and Science Village will make southern Sweden a world center in the field of material science, nano-technology, chemical sciences, and bio-technology. ESS will be funded and constructed by an international partnership of 17 European countries. Sweden, Denmark, and Norway are the host countries.

Commitment to Carbon Neutral

Waste Heat Recycling

One of the main motivations for Sweden to bid to be the host country was the commitment of ESS to be the world's first carbon-neutral large scale science facility. This commitment is in stark contrast to many other accelerator-based facilities in which large amounts of electrical energy are consumed by the accelerator and dissipated back into the environment. One of the cornerstones of the ESS carbon-neutral policy is the planned recycling of waste heat generated by ESS. The ESS site will consume power at a rate of up to 35 MW. It is anticipated that over one third of this energy will be recycled by heat exchanging the cooling water used to cool the ESS linear accelerator power systems with the district heating system of the city of Lund.

Superconducting RF Technology

Another cornerstone of ESS energy policy is the choice of advanced energy efficient technologies. ESS will be driven by the world's most powerful proton linear accelerator (linac). The ESS linac will provide an average beam power of 5 MW which is five times greater than the nearest competing facility. For the 600 meter long linac, 97% of the beam power will be supplied by superconducting accelerating structures that operate at -271C. At these low temperatures and with the niobium metal lining the walls of the accelerating structures, there is virtually no energy dissipated and almost all of the energy supplied to the accelerating structures is transformed into beam power.

Advanced RF Power Concepts

To power the ESS linac, conventional power from the grid must be transformed into an energy form suitable for filling the superconducting structures. The type of energy used in the linac is electromagnetic (or radio) waves oscillating at a frequency of 704 MHz. At most other accelerator facilities, the conventional grid power is transformed into RF power using devices called klystrons. The efficiency of these klystrons in operations is typically 35%. That is, for every watt of energy supplied to the accelerator, two watts are lost in the klystron to heat. As mentioned earlier, ESS plans on recycling a portion of this lost heat into the Lund central heating district. However, the engineers in the ESS Accelerator Division are spending over 5 million Euros to develop a new type of RF power source called a multi-beam induction output tube (MBIOT). The goal for this RF power source is to have an operational efficiency over 65%. A source with this efficiency could reduce the amount of waste heat generated by the accelerator RF systems by almost 50%.

Solar Energy

Currently absent from ESS energy policy is the use of solar energy; especially in the area of photovoltaics. However engineers at LTH and ESS Accelerator Division became aware of the use of large scale photovoltaic plants in relatively high latitudes in the Northern Hemisphere. There are at least 13 sites at latitudes greater than 50 degrees in Germany producing power in excess of 50 MW per site.[1] For example the pilot project of Ampegon GmbH in the Wertach Valley in southern Germany has been delivering over 20 MW of power derived by photovoltaics to power a large scale radio transmitter site.[2] The land used for the photovoltaics at the Wertach Valley site is underneath the radio transmitters. Because of the non-ionizing radiation hazards that are associated with these transmitters, this land is unsuitable for habitation or agriculture. Another feature of the Wertach Valley site is that the energy produced by the photovoltaic plant is used on-site. This example illustrates the two key features required for an economical photovoltaic plant.

Because of the low power density of solar radiation:

1. ***It is uneconomical to take land out of agricultural production or habitation to build photovoltaic power plants.***
2. ***Efficient photovoltaic plants should be located close to the sites where the energy is consumed.***

Solar Electricity Potential

Exploitation of solar energy in Sweden is commonly dismissed because of its high northern latitude. However, according to the Photovoltaic Geographical Information System (PVGIS)[3] the photovoltaic solar electricity potential for the ESS site in southern Sweden is 147 W-year/m^2. The yearly photovoltaic solar electricity potential is the amount of solar energy falling on a square meter of land averaged of a single year. As shown in Figure 1 and Figure 2, the solar energy potential in southern Sweden is comparable to most of the solar sites in Germany. Figures 3-7 show a comparison of the solar energy potential of Lund compared to other existing solar park sites at high northern latitudes. As shown in Figure 3, ***the solar energy potential of Lund is the same as the potential for largest photovoltaic plant in Europe*** which is Solarpark Meuro[4] located 130 km south of Berlin and generates 160 MW of peak power.

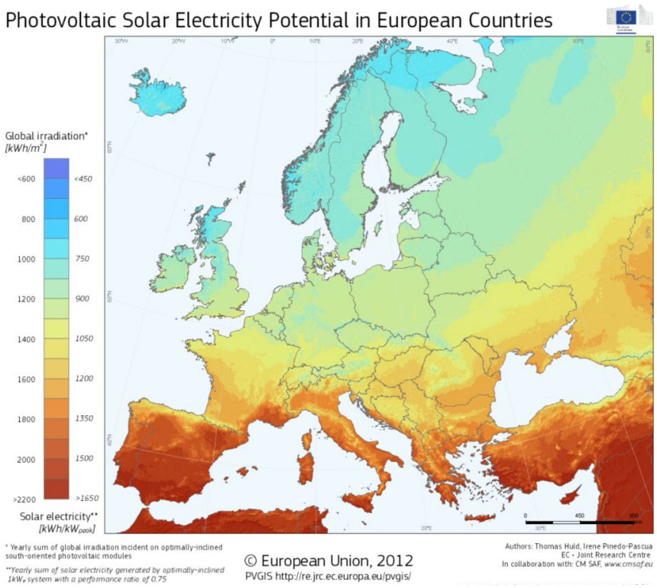

Figure 1. Photovoltaic Solar Electricity Potential in Europe

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[1] http://en.wikipedia.org/wiki/List_of_photovoltaic_power_stations

[2] http://www.ampegon.com/products/green-technologies/

[3] http://re.jrc.ec.europa.eu/pvgis/

[4] http://en.wikipedia.org/wiki/Solarpark_Meuro

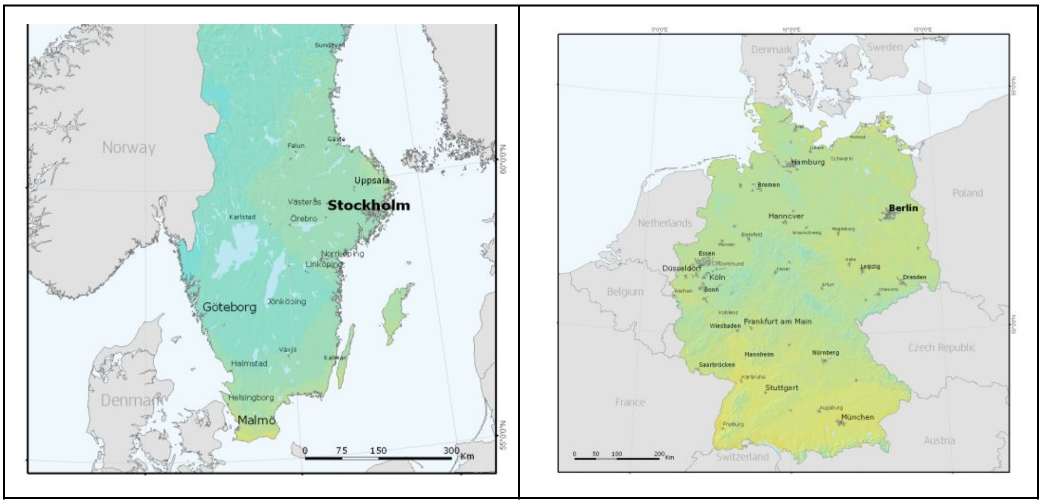

Figure 2. Photovoltaic Solar Electricity Potential Comparison between Sweden and Germany

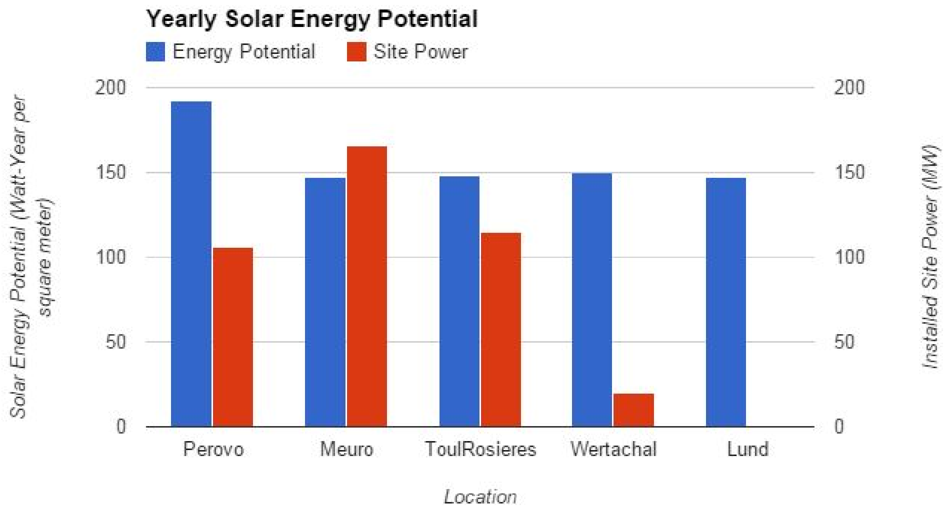

Figure 3. Yearly photovoltaic solar electricity potential at optimum inclination angle for a few selected sites.

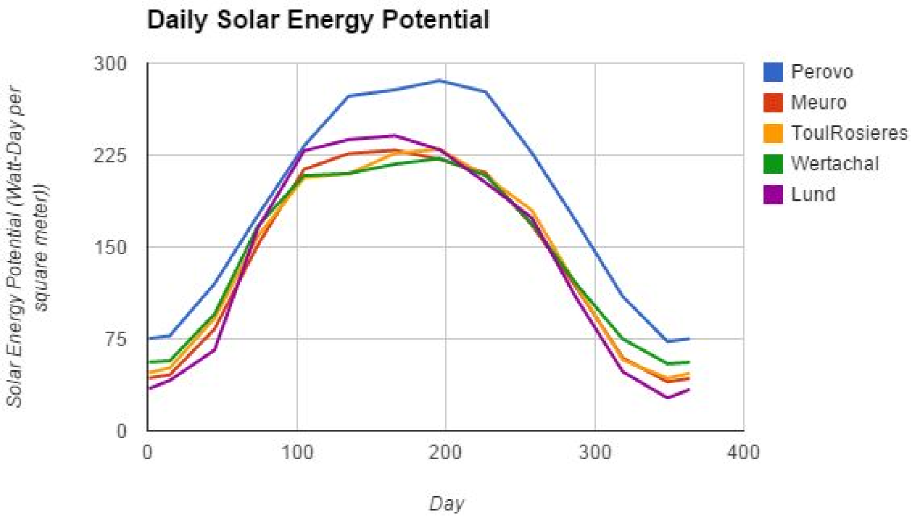

Figure 4. Daily photovoltaic solar electricity potential at optimum inclination angle for a few selected sites.

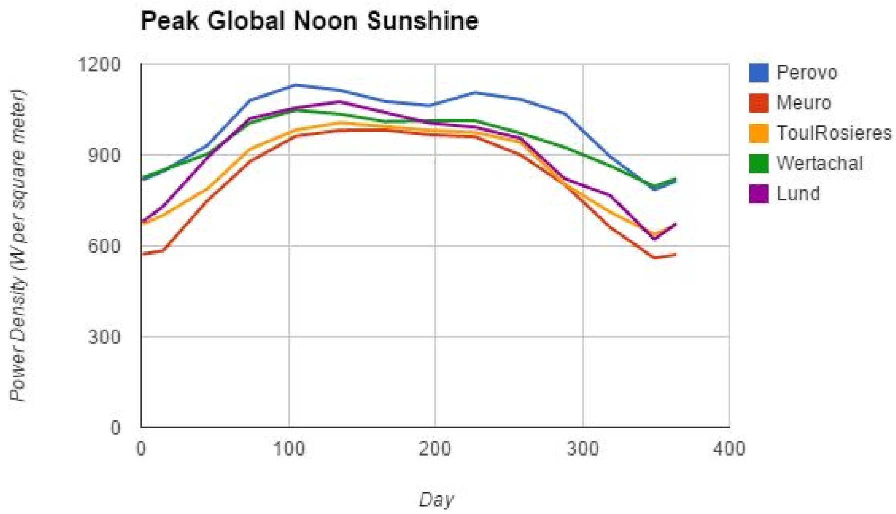

Figure 5. Peak solar radiation falling on a an optimum inclined panel at noon for various sites.

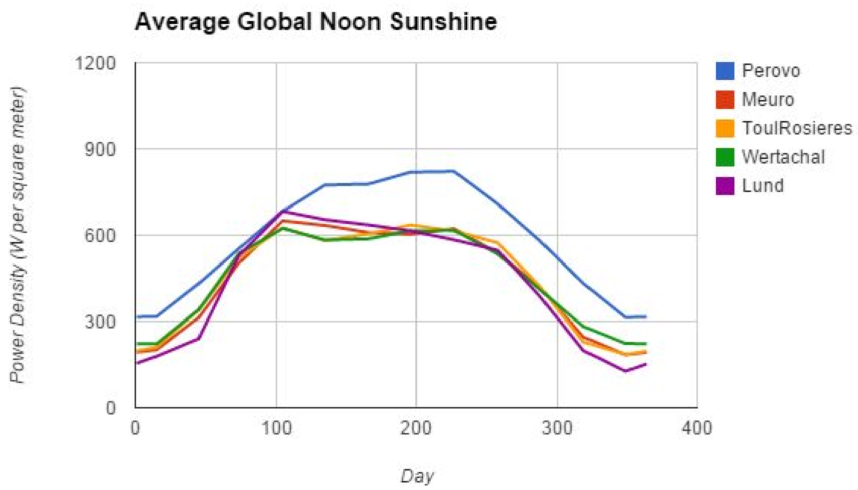

Figure 6. Average solar radiation falling on a an optimum inclined panel at noon for various sites.

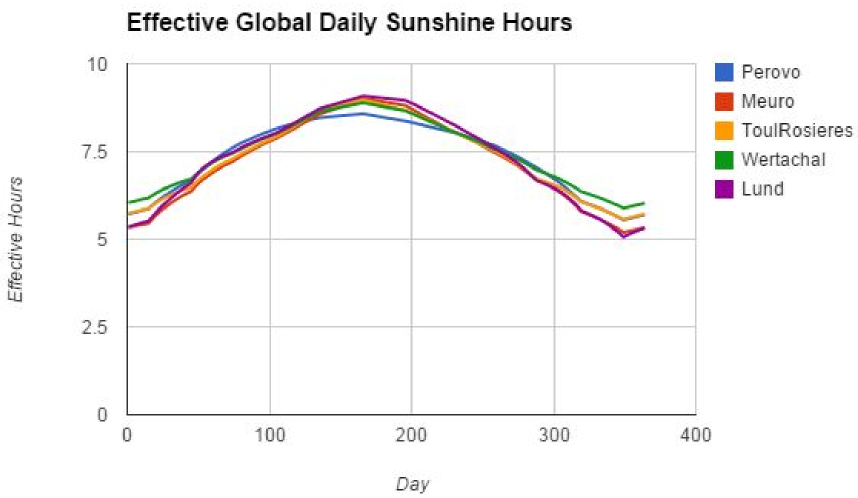

Figure 7. Effective daily sunshine hours. The product of the effective hours and the average solar radiation at noon (Figure 6) yield the daily solar energy (Figure 4).

Photovoltaic Solar Field at ESS

Available Land at the ESS Site

The ESS site occupies 74.2 hectares of land north-east of Lund. Because of the nature of hazards present at the ESS site, ***most of this land is un-occupied and used as a barrier to the general public and cannot be used for agriculture or habitation*** as illustrated in Figure 8. As shown in Figure 9, the amount of green space available for implementation of solar arrays is 27.5 hectares. In addition, building roofs and the accelerator shielding berm offer an additional 8.5 hectares. If the 5.1 hectares of empty space in the campus area that is enclosed by the ring road is utilized, the total amount of area available to a potential solar field is 41.2 hectares or 55% of the total ESS site. The solar potential for 41.2 hectares portion of the ESS site is over 60 MW-year/year. Because amount of energy required to power the entire ESS site is about 20 MW-year[5], the use of photovoltaics has the potential to contribute to a sizeable portion of the ESS energy needs.

Figure 8. Artist conception of the ESS site

[5] Assuming 5000 hours of yearly operation at a site power consumption rate of 35 MW.

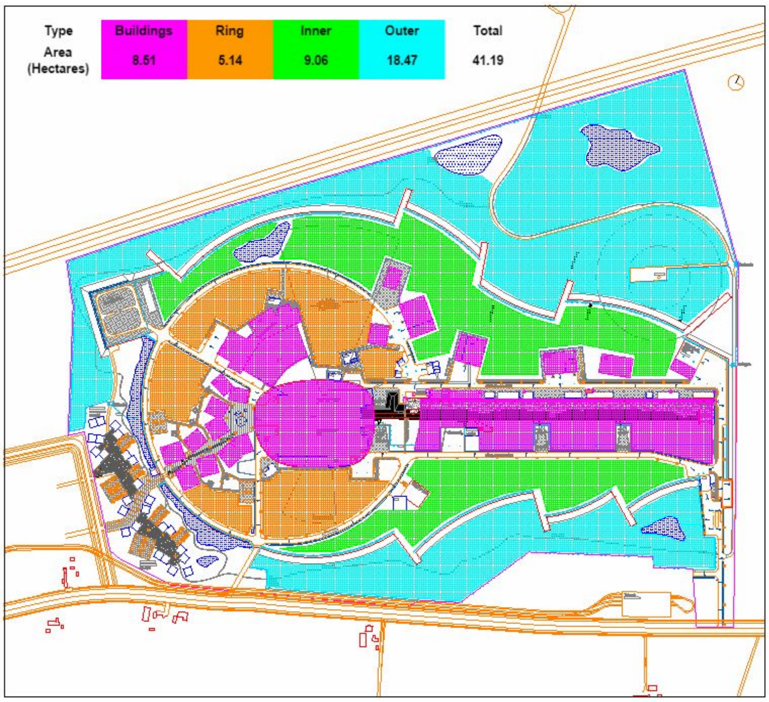

Figure 9. ESS Site Master Plan with possible locations for solar arrays.

Solar Electricity Distribution

Instead of transporting the photovoltaic energy off-site as in the case of most large solar parks, the photovoltaic energy collected on the ESS site can be directly consumed by the ESS linac. In the ESS linac, the accelerating structures will be powered by one hundred fifty 704 MHz transmitters. Each transmitter will be capable of delivering over 1 MW of peak RF power at an average power of 50 kW. The RF transmitters require special power converters that convert the conventional AC power provided by the electrical grid into pulsed waveforms that feed the electron guns that energize the RF transmitters. The special power converters are commonly referred to as “modulators”.

Because of the requirements of the ESS neutron target, the team comprised of engineers from LTH and ESS are developing a new type of modulator called Stacked Multi-Level Topology Modulator as shown in Figure 10. The main feature of this modulator is a parallel configured input charger and a series output voltage stack. The parallel input chargers keep the voltage at low levels (~ 1 kV) so that the precision control that is required by ESS can be achieved with standard components. The capacitor charger units consist of an AC/DC power converter (Active Front End) followed by a DC/DC power regulator that controls the voltage level to the modulator. At the junction between the AC/DC converter and the DC/DC converter, a multi string (array) of solar cells can be plugged in via a simple step-up DC/DC power converter providing Maximum Power Point Tracking (MPPT) with minimal electrical signal conditioning and cost. Indeed, the AC/DC Active Front End units of the modulators are based on the same power electronic structures as those of conventional solar inverters and is fully power reversible. This junction can be thought of as a three-way electrical valve in which:

- When the sun is shining, power is pulled from the solar cells to power the RF transmitters and minimal power is pulled from the electrical grid for regulation.

- When the sun is partly shining, power is pulled from the solar cells and the grid to power the RF transmitters. The AC/DC and DC/DC converters automatically regulate how much power comes from each source.
- When the sun is not shining, power is pulled automatically from the grid to power the RF transmitters.
- When the sun is shining and the accelerator is not running (when in a maintenance period), the power from the solar cells is back-feed to the grid to add additional power to the electric grid.

As long as provisions are made for this connection during the construction of the modulators, this ***connection to the modulator does not require any additional cost so that solar cells may be added at a much later date***.

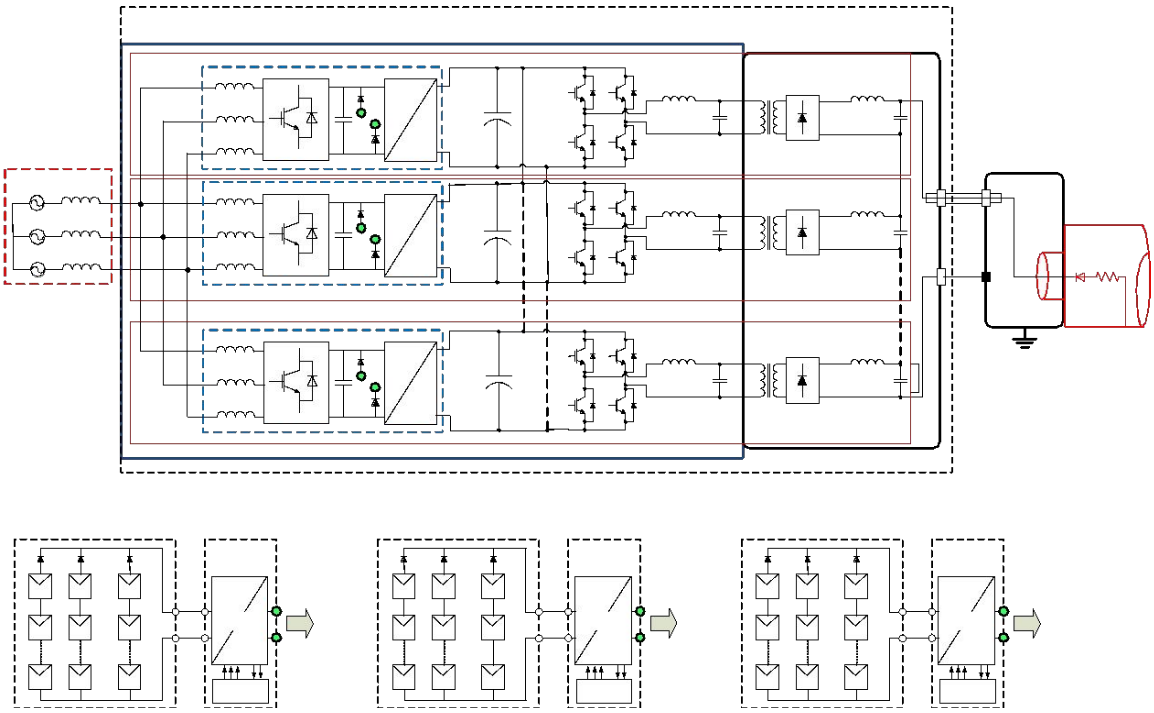

Figure 10. Stacked Multi-Level Topology Modulator

Optimum Land Use

The amount of land available at ESS is finite so there must be a compromise between the efficiency of the solar field and the amount of land the solar field occupies. A solar field will consist of rows of panels inclined to the south facing the sun at noon. These rows will be oriented along the east-west direction. To keep the adjacent rows panels from shadowing each other, there must be gaps between the rows. The fraction of the solar panel that will be shadowed by the panel to the south is a function of the panel inclination and the altitude of the sun over the horizon:

$$S_f(t) = \frac{1}{U_f} \frac{U_f sin(\theta) - \left(1 - U_f\right) cos(\theta) tan(\alpha(t))}{sin(\theta) + cos(\theta) tan(\alpha(t))} > 0 \qquad (1)$$

where θ is the inclination of the solar panel and $\alpha(t)$ is the altitude of the sun over the horizon as a function of time (t). The utilization factor, U_f, is the ratio of the area of land occupied by solar panels compared to the total area of the solar field. The shadow factor S_f(t) influences the the effective collecting area A_e(t)

$$A_e(t) = A_f \frac{U_f}{\cos(\theta)} \left(1 - S_f(t)\right) \quad (2)$$

where A_f is the total area of the solar field. Note that the definition of the shadow effect in the above equations is a pessimistic estimate because the equations do not take into account diffuse light. To minimize the shadow, the panel inclination should be low as possible while still collecting the maximum amount of sun.

Figure 11 shows the panel area required to produce 25 MW for a clear sky on the summer solstice in Lund (sun altitude of 58 degrees) as a function of the solar panel elevation (angle between a horizontal plane and the solar cell plane) and Figure 12 shows the total land area required as a function of utilization factor and elevation angle to produce a peak power of 25 MW. The yearly electrical energy output as a function of solar field size for various elevation angles is shown in Figure 13. Low panel inclination angles offer the most accumulated electrical energy for a given amount of land which is desirable since land space at ESS is limited. This result is due to the fact that shallow inclination angles minimize the shadow effect and since the received power is a function of the cosine of the difference between the elevation angle and the altitude of the sun over the horizon, the required panel area for 25 MW is a rather weak function of the elevation angle. However, low inclination angles require a higher utilization factor that could be problematic for installation and maintenance. A reasonable compromise is to choose an panel elevation angle of 10 degree and a field utilization factor of 70%.

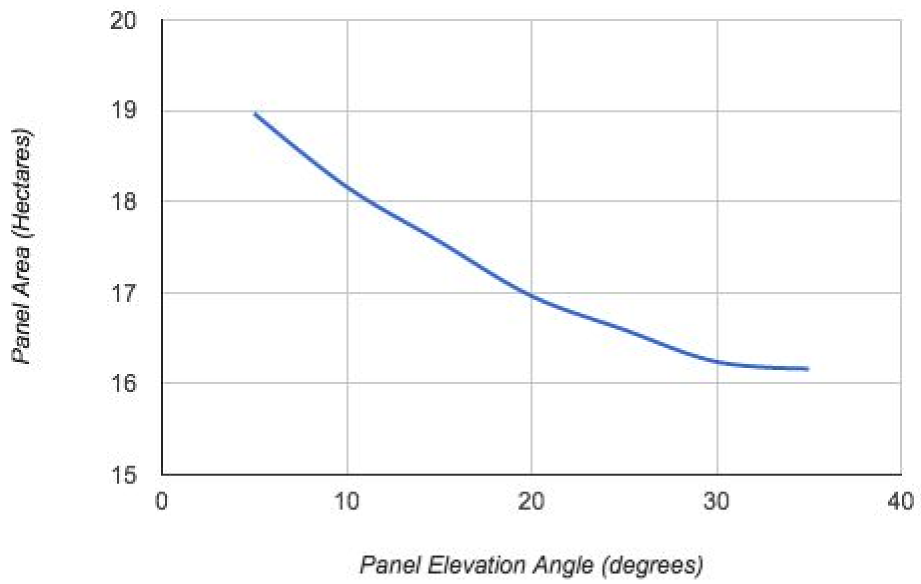

Figure 11. Solar panel area required to produce a peak power 25 MW at noon for a clear sky in mid-June in Lund with a solar panel efficiency of 17% and a transmission efficiency of 85% as a function of solar panel elevation angle.

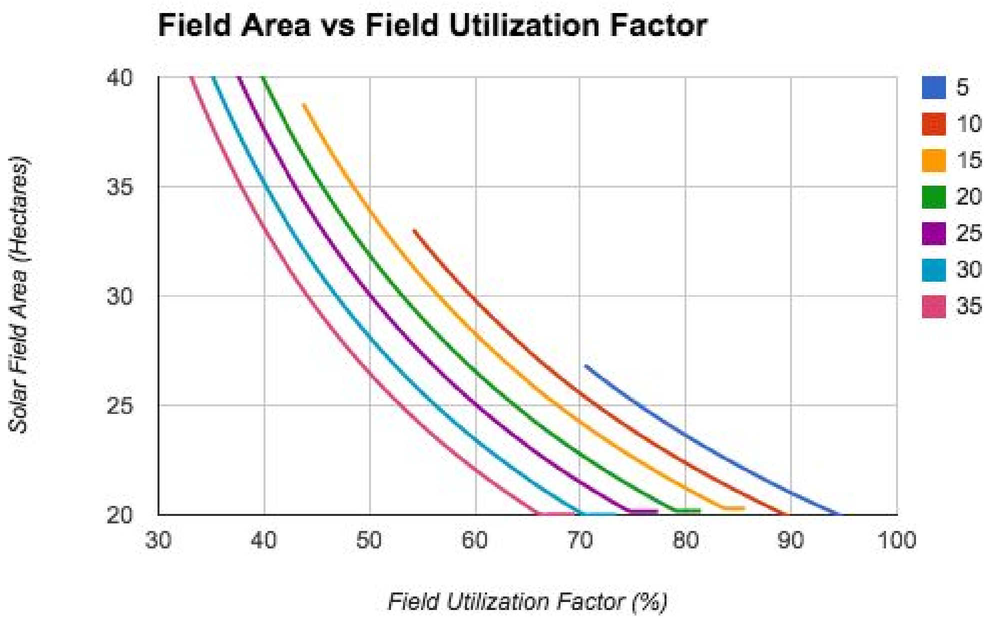

Figure 12. Solar Field Area as a function of Solar Field Utilization Factor for various elevation angles to produce a peak power 25 MW at noon for a clear sky in mid-June in Lund with a solar panel efficiency of 17% and a transmission efficiency of 85%.

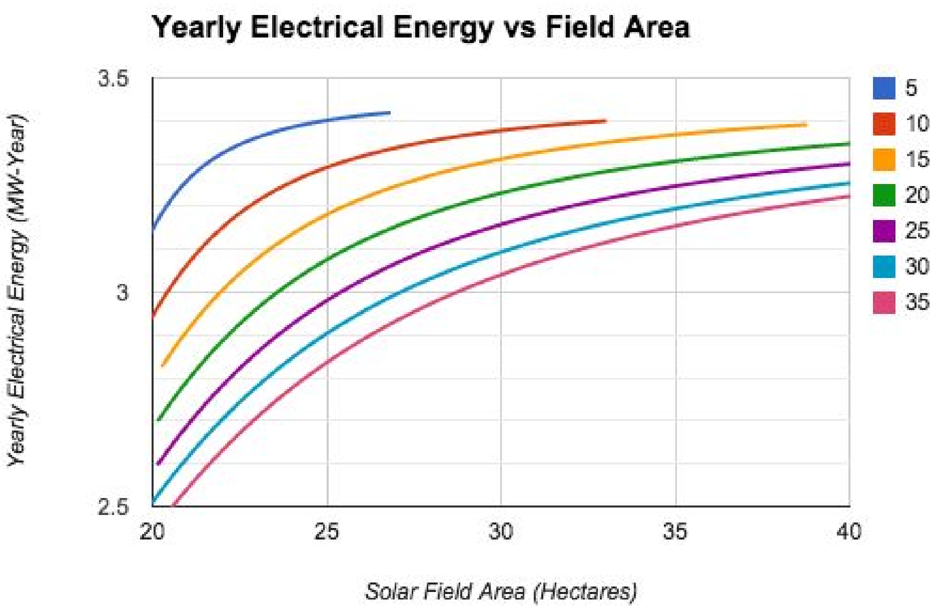

Figure 13. Total yearly electrical energy output vs total solar field area for various elevation angles for a peak power of 25 MW at noon for a clear sky in mid-June in Lund with a solar panel efficiency of 17% and a transmission efficiency of 85%.

23 MW Photovoltaic Solar Field

Since the solar field will power the modulators, the size of the photovoltaic plant will be limited by the peak power that the modulators can absorb. The current design of the ESS linac calls for thirty five modulators with each modulator rated at 650 kW giving a total power capability of 23 MW.

Table 1 shows the major design parameters for a 23 MW solar field. A photovoltaic efficiency of 20% was chosen because the current state of the art in photovoltaic efficiency is above 20%[6]. By the time the ESS solar field could be realized, it will be assumed that standard photovoltaic efficiency will be routinely above 20%. An electrical transmission efficiency of 95% was chosen because the electrical energy will not be transmitted off the ESS site and will be used locally by injecting the photovoltaic electrical energy into the heart of the ESS modulators. The amount of solar panels required is 13.6 hectares spread over 19.2 hectares which is 26% of the ESS site.

Field Area	19.2	hectares
Field Utilization Factor	70	%
Panel Inclination Angle	10	deg
Panel Photovoltaic Efficiency at 25C	20	%
Electrical Transmission Efficiency	95	%
Panel Area	13.6	hectares
Shadow Winter Solstice	25.7	%
Peak Electrical Power on Summer Solstice	22.75	MW
Daily Electrical Energy on Summer Solstice	6.3	MW-day
Yearly Electrical Energy	3.4	MW-Yr

Table 1. Proposed design parameters for a 23 MW peak power solar field for ESS

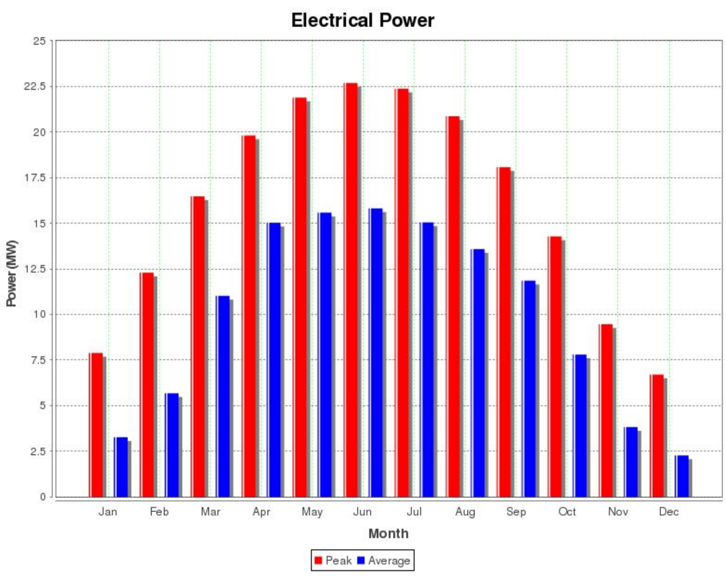

Figure 14. Average and peak electrical power collected at noon vs time of year for the solar field described in Table 1.

The electrical power received at noon and the daily integrated power is shown in Figures 14 and 15. Averaging over the entire year day and night, the average yearly energy of 3.4

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[6] http://www.pveducation.org/pvcdrom/appendices/solar-cell-efficiency-results2

MW-Year could be collected from such a field. Since the number of operations hours per year anticipated is 5000 hours, the solar array could provide for accelerator operations a yearly average rate of 6.0 MW ***which is more than enough to compensate for the entire amount of energy supplied to the beam***. Considering an electricity cost of 5 cents€ per kWh (industrial non-subsidiaries cost), the total energy yield of this photovoltaic facility would be about 1.5 M€ per year.

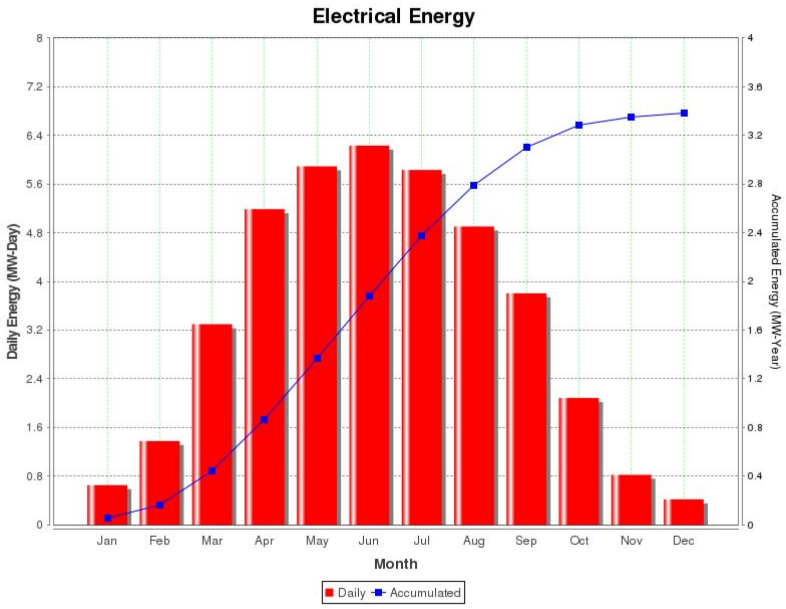

Figure 15. Daily and integrated electrical energy collected for the solar field described in Table 1.

Photovoltaic Energy Payback

The fabrication of solar panels is energy intensive. This energy is often pulled from non-green sources such as coal or other fossil fuel sources. For example, the melting of silica rock to obtain the silicon used in most panels requires electricity to fire ovens to a temperature of about 1700C. Because of rapidly changing technology, it is difficult to get an accurate accounting of the energy it takes to fabricate, deploy, and decommission solar panels. However, a rough estimate can be obtained by analyzing the Cumulative Energy Demand (CED) ratio compiled for solar panels as shown in Figure 16.[7] The CED is the ratio of the energy required to produce the panel including life cycle costs to the peak power the panel produces. The current state of the art CED for solar panels is about .45 - .57 years. A 22.75 MW field would require 10.2 - 13.0 MW-years of energy to produce. With an average electrical energy yield of 3.4 MW-years from the proposed ESS solar field, it would take 3 - 4 years of operations to reach the energy break even point. To decrease the payback time, the fabrication techniques and/or the efficiency of the solar panels must increase significantly.

[7] "Energy Balance of the Global Photovoltaic (PV) Industry - Is the PV Industry a Net Electricity Producer?," M Dale, S. Benson, dx.doi.org/10.1021/es3038824 | Environ. Sci. Technol. 2013, 47, 3482–3489

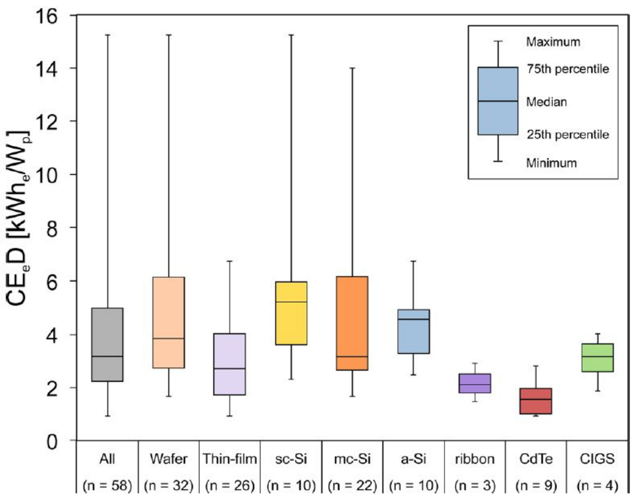

Figure 16. Distribution of estimates of CED of PV systems for a variety of technologies [7].

Hybrid Solar Field at ESS

Solar Energy Thermal Power

Solar cells are relatively inefficient at producing electricity. The solar array described above only converts 19% of the solar energy into useable electrical energy. The remaining 80% is lost in transmission, reflection, and heat. This uncaptured energy equates to 15.7 MW-years of energy per year for a fixed solar array. Because of the location of solar plants, either far from urban areas or in warm climates, most solar plants do not try to capture this heat energy. The biggest obstacle to using solar heat energy is the logistics of a distribution system for supplying heat. However, because of Sweden's commitment to reducing global warming and its climate, many communities in Sweden have adopted district heating systems to make substantial reductions in CO_2 emissions.[8]

Engineers at LTH and ESS have begun wondering if the district heating system in Lund could be utilized for distributing excess solar heat energy captured from photovoltaic panels that could be installed at ESS. Collecting heat from solar panels is a relatively established technology which involves flowing a fluid such as water or glycol through the solar panel to collect the heat and then flow the heated fluid through a heat exchanger to distribute the captured thermal energy. There are many companies on the market that provide photovoltaic and heating solutions but on a residential scale.[9] [10]

The major issue for obtaining both photovoltaic and thermal energy from solar cells simultaneously is the temperature at which the solar cells operate. For efficient distribution in district heating systems, the temperature of the water must be relatively high; on the order of

[8] http://www.svenskfjarrvarme.se/In-English/District-Heating-in-Sweden/
[9] http://soltechenergy.se/
[10] http://www.theengineer.co.uk/energy-and-environment/news/hybrid-solar-panel-heats-water-while-generating-electricity/1012110.article

80C[11]. Temperatures below 50C are inefficient for distributing heat and not as useful. However, the photovoltaic efficiency for semiconductors decreases with increasing temperature[12]. In the range between 0-150C, the efficiency of a solar cell as a function of temperature can be approximated as:

$$\eta(T) = \eta_{25C}(1 - K_L(T - 25C)) \qquad (3)$$

where η_{25C} is the photovoltaic efficiency of the of the solar cell at 25 C and K_L is dependent on the type of semiconductor of the solar cell. For polycrystalline silicon, a reasonable value for η_{25C} is 20% and for K_L is 0.0048 per degree[11]. For these values, the photovoltaic efficiency of the solar cell would drop from 20% at 25C to 14.7% at 80C. Operating the solar field described in the preceding section at 80C would drop the yearly photovoltaic yield by 27% so that the peak power that the solar field described in Table 1 could deliver would be less than 18 MW.

Field Area	26	hectares
Field Utilization Factor	70	%
Panel Inclination Angle	10	deg
Panel Photovoltaic Efficiency at 25C	20	%
Panel Photovoltaic Efficiency at 80C	14.7	%
Panel Temperature	80	C
Electrical Transmission Efficiency	95	%
Panel Area	18.5	hectares
Shadow Winter Solstice	25.7	%
Peak Electrical Power on Summer Solstice	22.75	MW
Daily Electrical Energy on Summer Solstice	6.3	MW-day
Yearly Electrical Energy	3.4	MW-Yr
Peak Thermal Power on Summer Solstice	138	MW
Yearly Thermal Energy	20.7	MW-Yr
Average Winter Thermal Energy (Oct-Mar)	8.8	MW-Day

Table 2. Proposed design parameters for a hybrid solar field for ESS that provides a peak electrical power of 23 MW and average thermal energy at 80C of 21 MW

To take full advantage of the klystron modulator infrastructure available at ESS, the area of the solar field would have to be increased to 26 hectares as shown in Table 2. As shown in Figures 17 and 18, the yearly thermal energy available at 80C for such a concept is 20.7 MW-years which is ***over five times the amount of heat planned to be recycled from the ESS linac***. The field provides a daily average of 8.8 MW-day for the months from October through March. The combined yearly electrical and thermal yield of the hybrid field is 24.1 MW-Years. Given that the entire ESS complex has a yearly energy consumption of less than 20 MW-years, the 26 hectare hybrid solar field can produce more 20% energy than ESS

[11] http://en.wikipedia.org/wiki/District_heating
[12] http://pveducation.org/pvcdrom/solar-cell-operation/effect-of-temperature

consumes. Also, the ***energy payback time drops*** from 3.5 years for photovoltaic only solar field described in Table 1 ***to less than 0.5 years for hybrid field***.

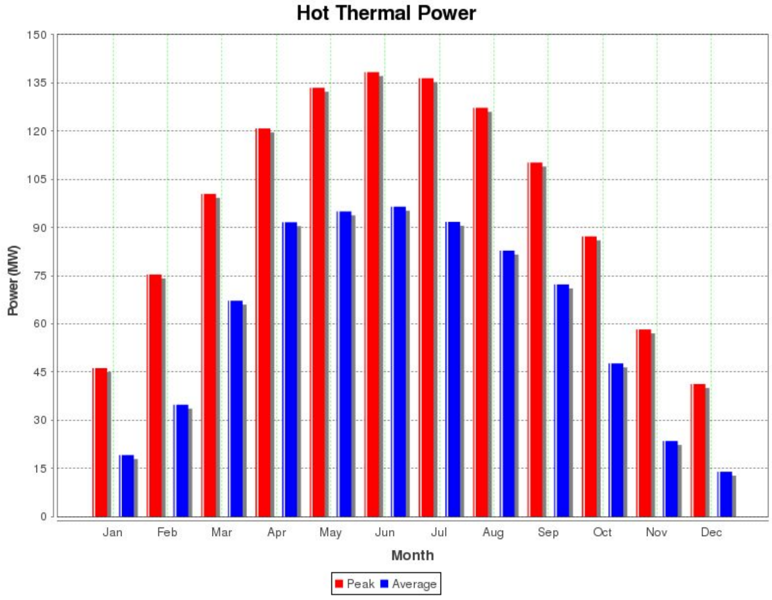

Figure 17. Average and peak thermal power collected at noon vs time of year for the solar field described in Table 2.

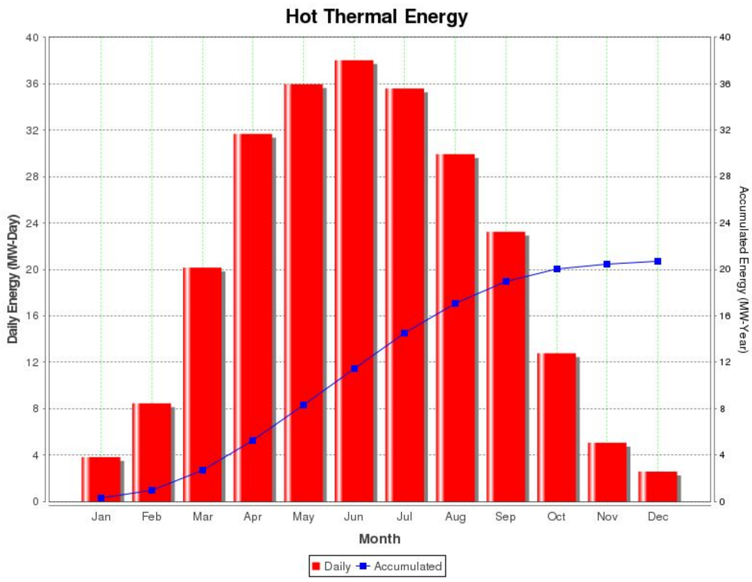

Figure 18. Daily and integrated thermal energy collected for the solar field described in Table 2.

Site Configuration and Project Staging

As discussed earlier, the photovoltaic electrical energy will be fed into the klystron modulators. There are 35 modulators and each modulator can consume 650 kW of peak power. The 26 hectare solar field can be divided into 35 mini-fields with each modulator fed by a single mini-field. Each mini-field will contain 0.53 hectares of solar panel spread over 0.74 hectares. Figure 19 shows a possible configuration of the 35 mini-fields.

However, ESS will be built in two stages. In the first stage which is to be completed by the end of 2019, ESS will be capable of providing with 1.2 MW beam power. The final beam energy of the linac will be 570 MeV and will be powered by 12 klystron modulators. At the end of the second stage, to be completed by 2023, ESS will be capable of providing with 5.0 MW beam power. The final beam energy of the linac will be 2000 MeV and will be powered by 35 klystron modulators. To match ESS construction, the solar field can also be constructed in stages. The first stage could consist of fourteen 650 kW mini-fields feeding 12 modulators as shown in Figure 20.

The solar field parameters for Stage 1 is shown in Table 3. Averaging over the entire year day and night, the average yearly electrical energy of 1.2 MW-Year could be collected from the Stage 1 field. Since the number of operations hours per year anticipated is 5000 hours, the solar array could provide for accelerator operations a yearly average rate of 2.1 MW which is more than enough to ***compensate for the entire amount of energy supplied to the beam in Stage 1 by a factor of 1.75***. The yearly thermal energy available at 80C for the Stage 1 field is 7.1 MW-years which is ***over six times the amount of heat planned to be recycled from the ESS linac***. The field provides a daily average of 3.0 MW-day for the months from October through March.

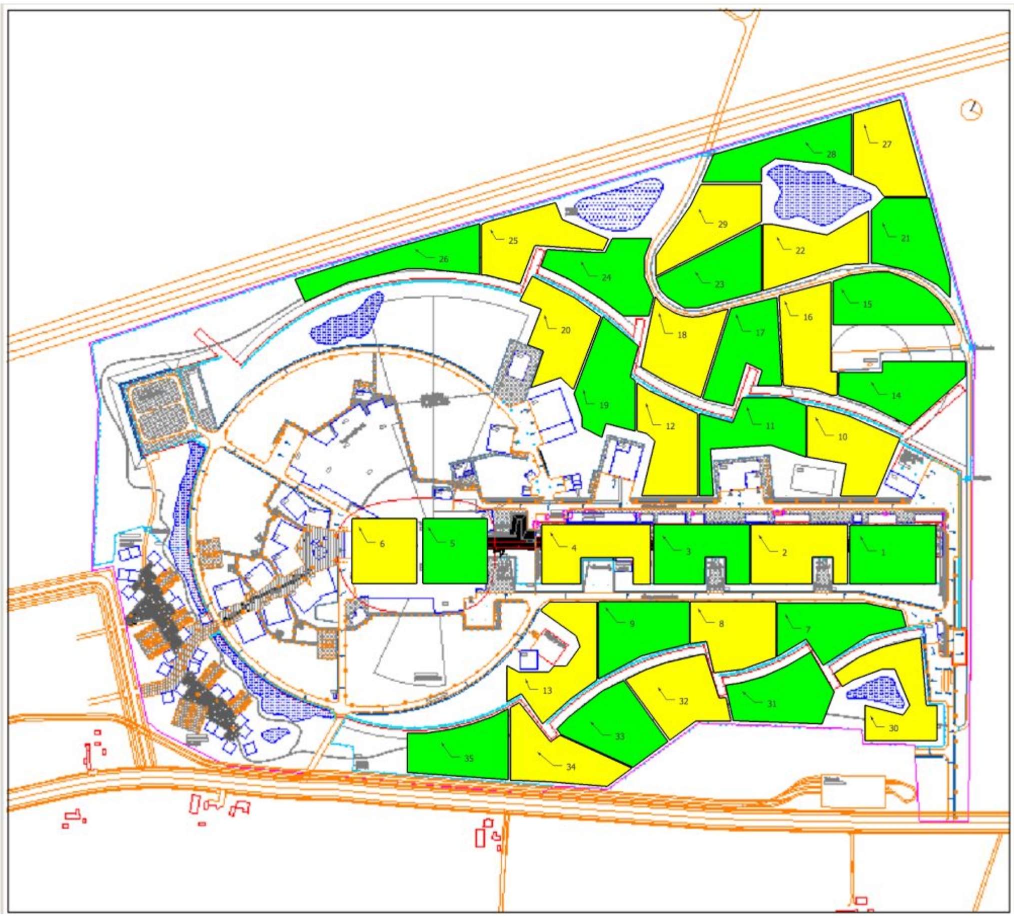

Figure 19. A 26 hectare solar field divided into 35 mini-fields

Figure 20. A 26 hectare solar field divided two stages.

Field Area	8.9	hectares
Field Utilization Factor	70	%
Panel Inclination Angle	10	deg
Panel Photovoltaic Efficiency at 25C	20	%
Panel Photovoltaic Efficiency at 80C	14.7	%
Panel Temperature	80	C
Electrical Transmission Efficiency	95	%
Panel Area	6.3	hectares
Shadow Winter Solstice	25.7	%
Peak Electrical Power on Summer Solstice	7.8	MW
Daily Electrical Energy on Summer Solstice	2.1	MW-day
Yearly Electrical Energy	1.2	MW-Yr
Peak Thermal Power on Summer Solstice	47	MW
Yearly Thermal Energy	7.1	MW-Yr
Average Winter Thermal Energy (Oct-Mar)	3.0	MW-Day

Table 3. Proposed design parameters for the first stage of a hybrid solar field for ESS that provides a peak electrical power of 8 MW and average thermal energy at 80C of 7 MW

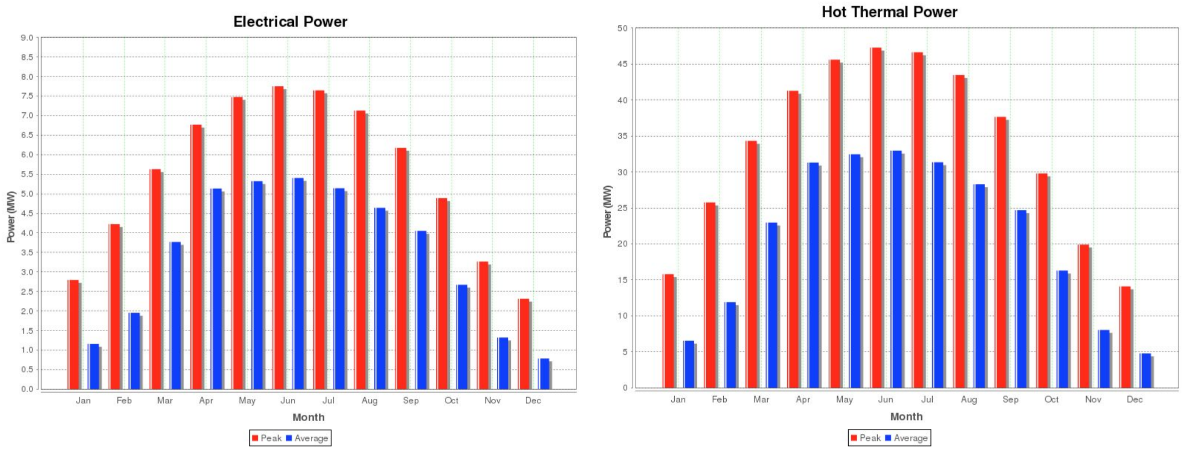

Figure 21. Average and peak electric and thermal power collected at noon vs time of year for the solar field described in Table 3.

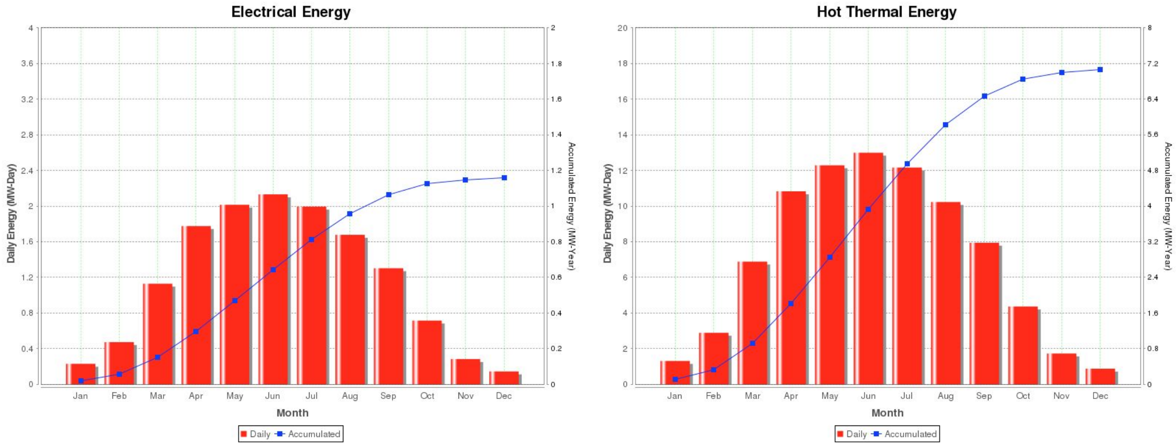

Figure 22. Daily and integrated electric and thermal energy collected for the solar field described in Table 3.

Conclusions

While the concept of hybrid solar panels is not a new idea, the use of hybrid solar panels on a large scale is a central idea of this note. Small scale hybrid solar installations such as rooftop panels are not as efficient as a large scale installations because of limitations in the site quality such as shadows and orientation and the cost and construction overhead of equipment such as pumps, power convertors, etc that is needed to service these installations.

Solar energy is a rather dilute form of energy and efficiency is the key to the exploitation of this energy. The physical proximity to users in both photovoltaic and thermal energy gathered from a hybrid solar field is exactly what is required for hybrid solar fields. Large scale hybrid installations are only possible in communities that have heavily invested on district heating infrastructure such as many communities found in Sweden. Also many of these communities in Sweden have unusable or undesirable land such as old factory sites, rail and shipping yards, dump grounds, etc, near their centers that would be ideal for hybrid solar fields that can directly tie into district heating systems.

In addition, these fields would be close to industrial manufacturing sites that could readily use the photovoltaic electric energy from the hybrid field if it is rendered in a form that is efficient for industrial use. Another central idea of this note is adaptation of modern power electronics to render photovoltaic energy into a useable form on a large scale that is in close physical proximity to users.

The nature of developing hybrid solar fields on a large scale might be daunting to many companies because of the size of the project and the risks involved. Building a prototype field at ESS in collaboration with industrial partners would go a long way to reducing these concerns and mitigating these risks because of the already available land and infrastructure that would be afforded at ESS. In addition, ESS is a scientific facility dedicated to the study of new ideas and should be more accepting of scientific and engineering challenges associated with a project of this size.

Future Work

A research program with its aim to develop a large scale hybrid solar field can be divided into manageable phases. The first phase would be an engineering study to explore the optimum configuration of a hybrid solar field including the logistics of electrical and thermal distribution. The next phase of the program could be the development of a technology demonstrator that would explore some of challenges into developing a large scale hybrid solar panel technology. A reasonable size for this technology demonstrator would be about 2% or a 15kW field. The next phase would be a prototype hybrid field on the 25% scale (150kW) in which aspects of distribution and load connections could be optimized. Finally, the last stage would be a pre-series demonstration in which a 650kW mini-field would be built.