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Green Accelerators? Lessons learned from ESS

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The costs of operating big science facilities, for example accelerators, are very large, and depend critically on the price of primarily electricity, but also of water and other utilities. This means that facilities must be energy and resource efficient. Facilities should at the same time also be environmentally sustainable. Finally, in these times with very high energy prices, all efforts must be made to keep the cost of operations at a reasonable level. In fact, these targets pull in the same direction. Efficient use includes not only the actual electrical efficiency of the existing equipment; it also means optimizing the *whole* facility for use of *all* energy. This will also help limiting the operations cost. At ESS a goal was to incorporate elements for sustainability already at the design stage in order to increase sustainability [1, 2]. ESS today sells excess heat to provide the local heating grid with energy, and provisions exist to use also lower-temperature water for heating purposes. The contribution will exemplify the trade-offs and considerations that were made, and what could have been implemented in a better way. A lot more can be done, and given the huge electrical power use almost any measure to save power will pay off quickly. The contribution will go over some of the possibilities and combinations that exist: Energy storage, solar panels, novel DC/DC converters to power equipment directly from solar panels, bio-fueled gas turbines, energy brokerage (buying electric power on term contracts to limit market exposure). ESS is also an active participant in various EU-programs that target sustainability, energy innovation, and flexible use of power [3, 4]. Many accelerator sites have large areas where for example solar panels or energy storage facilities can be installed. This kind of sustainability is part of the future for ESS. ESS also engaged in innovative projects for improved HV modulators [5] and multi-beam IOTs and klystron efficiency optimisation [6].

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1 Introduction

The ESS facility, under construction in Lund, Sweden, is set to become the newest neutron source in Europe starting from 2026 with the first experiments. ESS was planned to be a “green” facility. This paper will explore what steps were taken for this, how they worked out, and what lessons can be drawn from the project. We will also look at the future plans for sustainability at ESS.

In short, the sustainable aspects of ESS are the following:

1. The facility was planned to re-use and re-sell excess heat generated in the cooling system rather than to cool it off in a cooling facility
2. ESS pioneered some new developments that improves energy sustainable use and influence on the grid
3. ESS participates in two EU-Horizon programs where sustainability is a key aspect

The paper will detail some of the development work and results that were achieved so far.

2 Green design of ESS facility

ESS included various Green features both in the early plans and in the designs. It was a stated goal to sell excess heat to the district heating system rather than to cool it off. The project early adopted an energy design and an overall energy strategy [1, 2].

2.1 Cooling system

The major target was to recycle the excess heat as efficiently as possible. To facilitate this, a scheme where the cooling system separates the water in three different temperature categories was concieved: Low temperature (8 deg C input), Medium temperature (25 deg C input), and High temperature (45 deg C and upwards). All three ranges have controlled input of the temperature. Where required, the equipment cooled by the low and medium water have active control of the temperature, e.g. LLRF. Some parts of the accelerator have separate cooling skids that control to within a fraction of a degree C, e.g. RFQ. In these cases, the corresponding cooling range is used via a heat exchanger to cool off the heat. The temperature in the high section can reach 65 deg C or upwards. The initial design called for a temperature of 80 deg C. This allows direct transfer via heat exchanger to the district heating system. This plan led to a lot of internal dsicussions regarding the safety of running with 80+ degree water. The risk to soak co-workers with 80-degree water was evaluated and it was decided to lower the temperature in the hot cooling loop. Also, lifetime predictions at 90-100 deg C collector temperatures have not yet been attempted, although we suspect it would not be big issue..

Since the final temperatures can be lower than 80 degrees C heat pumps are sometimes used to lift the temperature. This in itself costs energy and it is therefore less efficient. After increasing the temperature to 80 deg C, ESS sells the heat to the district heating utility.

ESS not only uses the high temperature water, the low and medium ranges are used for heating as well. The central processing unit takes care of all the three water loops, and uses them for heating. Around the ESS site a new area for housing and scientific activity, Science Village, is built, and part of the heating of that area is prepared for heating via a low temperature district

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heating grid. Internally at the ESS site, the campus and the labs are heated using low and medium water, and in hot weather the low temperature range can be used for chillers/coolers.

2.2 Energy management

ESS manages energy supply via a mix of variable and fixed hedges towards the utilities. The hedges are based on projected energy consumption. That way, the best prices can be obtained. Future plans include expansion of this strategy to include own power production, Power Purchase Agreements directly with a producer, and market hedging to minimise ESS exposure to the energy market prices (currently very volatile).

The future possible power production can be using bio-gas turbines and solar panels. Energy storage to further reduce market volatility influence is also a possibility

Continued selling of excess heat is an integral part of the strategy for power supply. It is also clear that the selling of excess heat is dependent on the cost for ESS to make this heat available, and the agreements that have been made with the utilities – during hot summer if the energy price is negative, it may well be more advantageous to just cool away the excess heat.

2.3 Lessons Learned from the sustainable Design

Today, ESS is not yet operational, but we already recover and sell heat. During April 2023 half of the electrical consumption could be recovered and sold as heat (Fig. 1). It is a drawback that we cannot fully utilise the heat, but must spend energy to heatpump it to above 80 degree C. This is not as it was planned, and we are aware that we probably could have used higher temperature water (this does happen in various places). The risks for personnel were probably manageable, and it would have been possible to design a safe handling system for the water. We also experienced numerous issues emanating from the detailed specifications and interfaces of the water systems.

The main lessons are that for novel ways to do things extra care to detail is required, as well as a lot of contact with suppliers at an early stage to get them to committ to the specification that is desired.

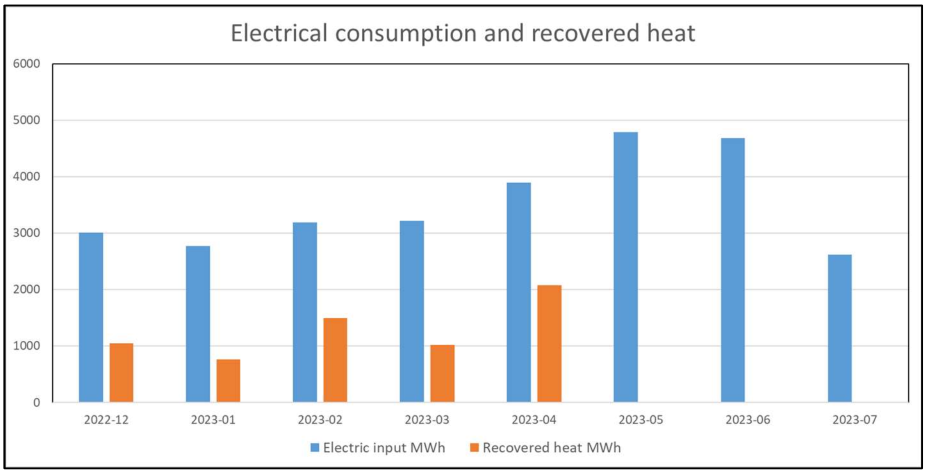

Figure 1. Supply and recovery of energy for ESS Dec 2022 to July 2023

3 New developments for sustainability

ESS has engaged in a number of innovative development programs to optimise cost and energy use of the facility. These include Stacked-Multi-Level modulators, Multi-beam IOT, and Klystron efficiency optimisation over a wide power range.

3.1 Stacked Multi Level (SML) modulators

Between 2014 and 2018, ESS developed and tested a novel modulator topology, SML, that is focused on avoiding flicker from the operation to propagate to the power feed. The topology employs active front-end and capacitor charge control. The design and testing constituted a major effort on the ESS side. The concept was then commercialised via tenders in an in-kind contribution. A modulator is shown in Fig. 2, and the performance in Table 1.

SML Topology performance
660 kVA at 115 kV/100 A, 3.5 ms pulse width (ca 5% duty)
Flicker <0.1% @14 Hz, efficiency 91%
High frequency ripple on flat top <0.15% (important for beam amp/phase control)
Footprint 3.8 m x 1.4 m
Cost ca 900 k€

Table 1. SML modulator performance

The modulators have small footprint and they are cost-effective. The power factor is close to unitary. The work is described in, among others, [5]. The use of these modulators also avoids having to use SVC compensators to take out the flicker and reactive power.

Figure 2. SML modulator in the ESS gallery.

3.2 Multi-Beam IOT

Klystrons were selected for most of the ESS linac to be the RF power source. Klystrons offer high saturated efficiency, but to cater for LLRF overhead the power must be rolled back, and effective efficiency is frequently below 50%. This means that the collector receives a lot of excess heat, and even if ESS recovers the heat, it would be good to not have to cool it away in the first place. IOTs do not require roll-back and can be overdriven without loss of efficiency. They also offer possible simplifications for the HV source, and can operate at lower HV than klystrons. We

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estimated to save roughly 10% of the energy required to run the accelerator at 5 MW beam power during operation.

To exploit the possible advantages with IOTs, ESS initiated a multi-beam IOT project and commissioned design and construction of two prototypes from Thales/CPI and L3. The project was run between 2014 and 2017. To reach the ESS specification, 1,2 MW peak power, multi-beam is required in an IOT.

The project was concluded successfully with two prototypes tested at 1,2 MW peak power, with 70% efficiency, and efficiency remaining above 60% down to 650 kW power (well above the 40-45% expected from klystrons). The IOTs were operated at a high voltage of 45 kV. Typical peak power and efficiencies are shown in Figure 3. The two IOTs are shown in Figure 4.

A more thorough evaluation of risks, costs, and benefits yielded however that IOTs brought more risks than advantages for the project. At 5% duty the payback time was too long (10 years or more) to justify further investment. The IOT work is described in [6] among others.

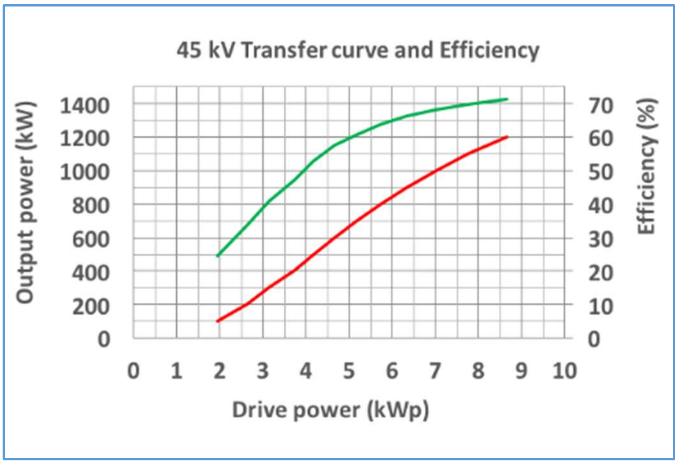

Figure 3. Efficiency and Peak Power for one of the IOTs

Figure 4. The two IOT prototypes

3.3 Optimisation of klystron efficiency

ESS employs 1.5 MW klystrons for the medium and high beta linacs. In the medium beta linac the klystrons are used for power levels ranging from 200 kW up to 1100 kW. At the lower power range the klystrons suffer a dramatic efficiency drop – the 45% becomes 10% at most. To improve energy management, this is mitigated by a combination of output cavity mismatch (planned already at tender stage) and a differrent operating point (lower HV). Using these methods the operational efficiency was raised from 10%-30% to 25%-50%. Only filling time considerations for the superconducting cavities prevented reaching 50% across the line. The projected energy savings are well above 10% of the energy required to run beam at 5 MW. This work is also described in [6].

4 ESS participation in EU projects

ESS is part of the EU Horizon programs iFAST and FlexRICAN [3, 4]. Both programs have as goals innovation and sustainability in accelerators, in line with ESS' general strategy in the energy field. As part of the work in iFAST, ESS has studied the addition of solar panels to the site, directly powering modulators from the DC side of solar panels. In FlexRICAN (to start March 2024), the main target is flexibility in energy supply, and subprojects cover among others renewable power generation (solar panels, bio-gas turbines), energy storage, optimisation of heat recovery.

Results from iFAST show that solar panels can provide a sizeable fraction of the energy need. Covering only the accelerator berm could save 5-10% of the yearly energy need, and the site has room for a lot more panels. It is, of course a trade-off between cost and benefit. DC/DC converters were explored for direct DC powering of HV modulators, and we saw that this can save 3-4% of the energy.

ESS has taken the project co-ordination role in FlexRICAN, and will focus on solar panel set-up, DC/DC converters for direct powering of HV, excess heat recovery optimisation, and contribute to energy storage work.

5 Summary

ESS was planned and designed with sustainability in mind. Some of the early plans were successfully executed (selling excess heat and active supply strategy); some lay in the future (local storage and production, diversified supply strategy). Some technical innovations were successfully executed (multi-beam IOT with higher efficiency, efficient and flicker free HV modulator, optimization of klystron efficiency). All of the plans and designs required some modifications in order to work out.

Some lessons were that it is good to be careful about the interfaces and the detailed specifications – these can trip up the best laid plans. Get suppliers to buy in early in the procurement process.

Finally, participation in programs across facilities generates a lot of added value.

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