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RESEARCH ARTICLE

# Low-grade heat recycling for system synergies between waste heat and food production, a case study at the European Spallation Source

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## Abstract

At present food production depends almost exclusively on direct use of stored energy sources, may perhaps they be nuclear-, petroleum-, or biobased. Arable land, artificial fertilizers, and fresh water resources are the base for our present food systems, but are limited. At the same time, energy resources in the form of waste heat are available in ample quantities. The European Spallation Source (ESS) will require approximately 270 GWh of power per year to operate, power that ultimately is converted to heat. This multidisciplinary case study details an alternative food production cooling chain, using low-grade surplus heat, and involving fermentation, aquaculture, nutrient recapture, and greenhouse horticulture including both use of low-grade surplus heat and recycling of society's organic waste that is converted to animal feed and fertilizer. The study indicates that by combining the use of surplus energy with harvest of society's organic side flows, for example, food waste and aquatic-based cash crops, sustainable food systems are possible at a level of significance also for global food security. The effects of the proposed heat reuse model are discussed in a system perspective and in the context of the UNSCD indicator framework. The potential sustainability benefits of such an effort are shown to be substantial and multifaceted.

## Introduction

### The opportunity to recycle low-grade heat

In recent years, there has been a substantially increased research effort into the use of low-grade waste heat. The driver behind this interest seems to be the combination of concern of the climate impact from energy use and the substantial supply of low-grade heat. Low-grade heat is plentiful, because it is a by-product of thermal power production as well as various industrial processes in sectors such as metals and pulp and paper. In the United Kingdom, 11.4 TWh of recoverable heat was found to be wasted each year [1]. However, this figure only represents the wastage where there is a technically viable use available. The total amount of wasted heat is 48 TWh per year [2]. Similarly, "In the USA, over two-thirds of the primary energy supply is ultimately rejected as low-grade waste heat" [3]. Sweden, considered a world leader in heat recycling with its well-developed district heating networks, reuses 4 TWh of 9.5 available industrial waste heat [4]. This figure does not include the considerably larger waste heat streams from nuclear power.

An emerging source of low-grade waste heat may be data centers. In these, "temperatures as high as 60°C are sufficient to cool microprocessors" and "switching to liquid cooling [is] inevitable" [5]. This would lead to two improvements, greater efficiency in the data center and the possibility to utilize the waste heat.

Certainly, the need to address the climate impact of world energy supply is well established. The concept of "energy poverty" also pinpoints a need to address energy efficiency from a viewpoint of economy and equity. The recovery of low-grade heat has been shown to be able to play a role in this and the opportunities for doing so seem to be increasing [6]. A low-temperature district heating network greatly facilitates heat recovery from industrial waste heat and leads to more efficient industry, cheaper heat, and lower emissions [7].

## Purpose of the research

There is thus significant indication of an opportunity to create sustainability benefits by recycling low-grade heat. The purpose of research is to contribute to knowledge about how low-grade waste heat can be used in ways that are both practicable and sustainable. Target audiences for this article are sustainability managers, energy managers, government bodies involved in planning and energy systems, and researchers in the field.

To achieve the research goal, based on the identified case, the following research questions were posed:

1. What uses for industrial waste heat have been identified with development potential?
2. What are the identified sustainability benefits of the identified heat-recycling initiatives?
3. What potential sustainability benefits and costs might be associated with the heat recycling and how may they be evaluated?

## Methods

This research is based on an in-depth case study. The organization in the case, the European Spallation Source (ESS) is large-scale, multinational research facility, a type of institution often called "research infrastructure." The study of research infrastructure offers some advantages. As organizations dedicated to facilitating scientific endeavor, research infrastructure tends to be default support research and to be open to the study. They tend to have an academic culture and publish design reports and other documents, and work with peer review as a management process [8]. Energy issues in research infrastructure have in recent years also attracted considerable interest [9].

The case is of special interest because ESS has committed to recycling its waste heat, and doing so in an as efficient way as possible. The commitment is strong, having been made between partner governments.

To achieve its goals, the ESS has formed a close collaboration with the Swedish University of Agricultural Sciences (SLU) and other interested parties, and has developed a proposal, based on the biological systems to reuse low-grade heat, which is detailed in the case study.

The case is analyzed in the perspectives of the interaction of the involved systems and sustainability impacts of the case proposal in these systems. In the systems perspective, the point of departure is the effect in the case on the energy system, and the analysis continues with connections to food and nutrient systems and water.

Many tools and indices to assess sustainability have been proposed, and these proposals have in turn been analyzed. In one such sustainability indices, the authors conclude that "We show that these indices fail to fulfill fundamental scientific requirements making them rather useless if not misleading with respect to policy advice" [10].

Indices do not express objective truths, but instead are powerful expressions of a chosen set of values [11]. "Indicators arise from values (we measure what we care about), and they create values (we care about what we measure)" [12] and further "from a scientific point of view, there cannot be such a thing as one comprehensive measure or index of sustainability" [13, 14].

Therefore, the sustainability assessment will focus on identifying the relevant categories of sustainability impacts and discussing the case from a systems perspective in these categories. Rather than attempting to assess the proposal into an index figure, the case is discussed in the context of each relevant theme in the framework put forward by the United Nations Commission for Sustainable Development [15].

## Structure of the article

This first section of this article serves to introduce the issues and thereafter to present the purpose of the research and the methods employed to attain them. The rest of the article is structured as follows: "Use of Low-Grade Heat in the Literature" section contextualizes the study by giving a brief overview of uses of low-grade heat from the literature. Section "Case Study: The European Spallation Source" thereafter presents the case study, starting with the organization studied, its goals, and operating conditions as well as design solutions implemented at the point of study. Relevant local market and climate conditions are also briefly presented. Section "Proposal: waste heat for food production with a nutrient loop" contains a presentation of a proposal for improved heat recycling at lower temperatures that included integration to horticulture and aquaculture. Section "Analysis" is the analysis of the findings in the case, starting with the general applicability of the case study to industry, thereafter applying a systems perspective and lastly a sustainability perspective. And the final section presents the main conclusions of the study.

## Use of Low-Grade Heat in the Literature

### Potential uses of low-grade heat

The simplest use for low-grade waste heat is for space heating. Today, temperatures as low as 40°C can easily be used for heating purposes, either via ventilation or floor heating. The environmental benefits of this can be substantial, if the waste heat replaces burning of fossil fuels. Looking at waste heat in the United Kingdom, "one-third of all fossil fuels consumed in the UK to produce low-grade heat for buildings" and further that "district heating schemes can provide cost-effective and low-carbon energy to local populations" [16]. The word "local" is significant. Heating, as opposed to electrical power, can be relatively easily stored, but is difficult to transport. Therefore, "direct heat use will depend on whether [a] potential user can be found" [6].

Aside from residential space heating, low-grade heat may also be supplied to greenhouses. However, as a cooling source for industry, greenhouses are viable only in winter, or in very northern climate areas [17].

Heating demand for greenhouses in Sweden is around 0.5 TWh [18, 19]. Nonetheless, reducing the sustainability impact of energy use would be a significant improvement of the sustainability performance of greenhouses. Also, "energy is typically the largest over-head cost in the production of greenhouse crops." Counting indirect energy use, fertilizer is one of the most energy-consuming parts of greenhouse operation, accounting for 21% of energy use [18].

Greenhouses contribute to sustainable development by vastly increasing the yield for a given area. The increase can be by a factor of 10–20 times compared to outdoor horticulture [18].

An intriguing possibility is to generate electrical power with waste heat. The most common proposal for this to make use of the organic Rankine cycle (ORC), but many other proposals exist, such as Stirling engines or condensing boilers [1, 20]. Suppliers of ORC systems claim to be able to produce power at temperatures such as 80°C and even lower, but typically require a heat sink with a temperature difference to the supply of at least 40°C. Moreover, at these extreme levels the production is not very economical. Other systems tend to demand higher temperatures and/or higher temperature differences. According to Fang et al. [7], industrial uses of waste heat include desalination and power generation, but are difficult at temperatures under around 200°C.

It would seem more advantageous to find uses of heat not requiring conversion to mechanical or electrical power. There is a significant difference between *recovery* and use as heat or *upgrade* to work, electricity or cooling [3]. Aside from space heat, refrigeration and desalination allow direct use without conversion to mechanical work [5]. Desalination can be achieved at as low temperatures as 45–50°C using "near vacuum level pressures" [6]. Even freezing is possible [21]. The much-awaited hydrogen economy would open up new possibilities, such as biohydrogen via dark fermentation at 70°C [22], or biohydrogen and biomethane at 37°C [23]. Additional uses include bacteria growth, typically at 37–38°C, biogasification, drying biomass, and production of a variety of substances, including ammonia, hydrogen, and pure water [6].

The drying process can have a crucial impact on the total energy efficiency of the use of biomass as an energy carrier, because the drying requires significant amounts of energy. Similarly, in digestion processes, digestibility has been shown to increase by 5–10% when the temperature is increased from 35°C to 50°C, but the energy use for heating was higher than the gain [24]. Production of protein meals for constructed animal feed from biomass sources as fish, microbes, macroalgae, plants, and insects require energy for drying. For example, meal production from as varying sources as yeast or fish requires removal of more than 70–80% of the weight in water [25]. Traditionally, high-temperature systems with temperatures over 100°C have been used, but more recently it has become clear that lower drying temperatures improve the quality of the product [26]. Today more than 27 million tons of fish is processed into fishmeal annually [27, 28] requiring removal of nearly 20 million tons of water. Considering the prognosis of more than 90 million ton of farmed fish to 2030 [28] and a replacement of soy as the major protein source in their diet with single cell protein (as yeast, microalgae etc.), macroalgae, feed mussel meal, and/or insects, more than 300 million tons of water needs to be evaporated by low-temperature drying techniques in order to form a transportable commodity to be used in the aquatic feed production. Even if fish has an uniquely high protein need, the amounts will be similar or even larger in the terrestrial farmed animals considering their larger volumes and that also in these animals the use of human grade protein sources (mainly soy and corn) must be replaced by alternative sources like the ones mentioned earlier and thereby require more energy for evaporating water than presently is the case. Considering that 1 kg of water requires 2.3 MJ for evaporation, it becomes clear that alternative techniques to the present ones based on fossil energy are urgently needed.

Production of fish and microalgae in more closed systems will require heating, especially in temperate climates. The need of energy will vary with farming temperature, exchange of water, and ventilation. Salmon requires 14°C as the optimal temperature, while tilapia prefer close to 30°C. Most fish will have a Q10 of more than a doubling and, for example, will salmon smolt double their growth already when temperature is increased from 9°C to 14°C [29, 30]. On the other hand, fish, in parity with all biological organisms, are more sensitive to a temperature above their optimum than to a lower one [31]. In a complete flow through system roughly 70 $m^3$ of water is needed per kg of salmon production, while about 2/3 is needed in less oxygen-demanding and $CO_2$-resistant species [32]. Given input of oxygen and $CO_2$ stripper, this requirement could be reduced to 50% and with high-technology filtration, protein skimming, and biological filters a reduction to 2.5% is possible [33]. However, in most food production system an exchange below 15% of farming volume per day is unusual due to quality reason. A quick calculation then gives with hand that a standing biomass of, for example, 1000 ton, with a density of 50 kg/$m^3$, will require a total farming volume of 20,000 $m^3$. An ambient water temperature of 10°C and a farming temperature of, for example, 25°C would require at an exchange of 15% heating of 3000 $m^3$ at 15°C per day.

### The importance of temperature

Temperature is fundamental to heat recycling: "The temperature of the low-grade heat stream is the most important parameter, as the effective use of the residual heat or the efficiency of energy recovery from the low-grade heat sources will mainly depend on the temperature difference between the source a suitable sink, for example another process or space heating/cooling" [6].

Within the literature discussing recycling and use of low-grade heat, there is variance in the definition "low grade," including the "widely accepted threshold temperature": 250°C [6, 20], 260°C [1], 60°C, and 120°C [3], and a typical heat from a solar collector (70°C) [21].

## Case Study: The European Spallation Source

### The European Spallation Source

The European Spallation Source (ESS) is a large-scale research facility in construction in Lund, Sweden. The facility will supply neutrons and a suite of neutron instruments for use in research in materials, life science, energy, and other disciplines. The facility will generate a far stronger neutron flux than existing facilities. To generate the flow of neutrons, a linear proton accelerator, the most powerful in the world, will propel bunches of $10^{12}$ protons into a target in the form of a large wheel of tungsten. In this target, the spallation process takes place, generating 30 neutrons for every proton.

Neutrons, being neutral particles, can penetrate into materials and can be used to create images of the insides of materials and substances on a nanometer scale and with nanosecond resolution. Neutrons are particularly useful for investigating light atoms, such as hydrogen, carbon, and oxygen found in organic molecules. This makes neutrons an important tool within life sciences, sustainability, and energy research. Within energy specifically, neutrons can help study the movement and structure of ions in batteries and fuel cells. The storage of hydrogen in metal substrates is another active research area, as is carbon capture and storage. With somewhat different research methods, neutrons can also be used to investigate photovoltaics and photosynthesis. The ESS and similar facilities can be used for in situ studies, typically looking at ongoing combustion processes to explore mechanical and chemical process improvements. A highly specialized area of research is superconductivity. This research makes use of another property of neutrons, their magnetic spin, to explore how magnetic properties of materials change with temperature.

### Development of a sustainability strategy

The decision to build ESS in Lund was preceded by a competition between countries to host the facility. It was in this competition that the host governments of Sweden and Denmark committed to building a sustainable research facility, by implementing and energy strategy called Responsible, Renewable, and Recyclable. This meant that the facility was to be energy efficient, use energy from renewable sources, and recycle the waste heat resulting from activities. Importantly, this trio of goals was given as a hierarchy, so that energy efficiency was of higher priority than heat recycling [34].

The three parts of the energy strategy were given specific requirements in an Energy Policy [35]. The target for energy efficiency was set for a maximum of 270 GWh total annual energy use at full operation. The target for Renewable was that all energy used would be from renewable sources, and for Recyclable, it was that all "recuperated" waste heat would be reused. "Recuperated" meant heat captured in cooling systems.

ESS Scandinavia, as the Swedish and Danish bid to host was called, also proposed a shift to an almost completely superconducting linear accelerator, which was a significant gain in overall efficiency at ESS. A superconducting accelerator does not suffer from losses due to resistance in the accelerator, but requires cryogenics to chill the accelerator to approximately 2 K, in itself an energy-intensive process. Despite this, superconducting was still a net gain. This technological leap also had an important effect on heat recycling, as the cryogenics is required to run constantly, in order to preserve the cryogenic helium and to avoid thermal expansion in the accelerator, which would require time-consuming retuning. Therefore, a superconducting accelerator requires a constant minimum cooling, and thus supplies a constant minimum flow of heat.

The original energy concept envisioned heat recycling to the local district heating system. This system supplies Lund, as well as neighboring townships with a total of around a TWh of heat per year. Additionally, the operator has embarked on a project to connect this system with more distant heating systems in neighboring cities. However, district heating systems typically operate at temperatures of 80–120°C, whereas cooling systems for accelerator-based research facilities typically have cooling loops at two levels, one cooling-tower level of 30–40°C and one chilled water level of 5–20°C. Technically, this gap could easily be bridged with the use of heat pumps, but to do so for the full heat load at ESS would have directly conflicted with the "Responsible" goal of energy efficiency.

Since before the ESS Scandinavian proposal, ESS Scandinavia, and subsequently ESS has been collaborating in various agreements with the district heating operator Lunds Energi (now Kraftringen) to pursue a sustainable research facility. Throughout this long-term collaboration Kraftringen has been pursuing an independent effort to reduce temperatures in it local district heating system to reduce losses. As of December 2013, the two parties have reached a formal agreement to connect ESS to the district heating system. This agreement requires ESS to provide a temperature of 80°C, which is deemed sufficient for heating needs. The ESS receives back a temperature of under 50°C.

The evolution of the ESS energy strategy has been analyzed in sustainability strategy research [36].

## Energy inventory

ESS has implemented a program to raise cooling temperature levels, in order to make use of the district heating system directly as cooling, an effort that has led to attention in the field [9]. High-temperature cooling is being implemented primarily for the klystrons providing the accelerating power and for the helium compressors providing the cryogenic cooling. Nevertheless, a significant amount of cooling is still necessary at lower temperature levels. The energy inventory, a biannual exercise conducted at ESS shows the projected energy use as well as the cooling needs at the three temperature levels.

The latest available energy inventory [37] shows a total annual power use of 265 GWh, of which 60 GWh is for the heat pumps that provide the lower temperature cooling and eject heat to the district heating system. The estimated total recovered heat amounts to 253 GWh per year, divided into temperature levels according to Table 1.

**Table 1.** The cooling temperature levels at ESS.

| Temperature levels | Supply temperature (°C) | Return temperature (°C) | Part of total (%) |
|---|---|---|---|
| Low | 5–15 | 30–35 | 30 |
| Medium | 30–35 | 40–50 | 35 |
| High | 40–50 | 75–80 | 35 |

The possible savings from recycling heat at lower temperatures than the 80°C required for the district heating system are thus significant.

## Sustainability issues aside from energy at ESS

The indirect effect of energy was considered the most important and variable sustainability issue at ESS, but of course there were others as well. The facility would generate substantial volumes of radioactive waste, albeit mostly at rather low levels. Radiation protection was an important issue. Radioactive waste handling and radiation safety issues were dealt with a regulatory framework.

An issue that came up in relation to local inhabitants and in conjunction with the regulatory process was the use of 60 ha of prime agricultural land for the construction of the facility. This had led to some local opposition in the licensing process from the local farmer's organization and a local nature conservation organization. Placing this large facility on such excellent soil was perceived as unsustainable and a threat to future food security.

## Indicative prices in the case

A full business case for heat recycling alternatives was not yet available, but some indicative prices could be uncovered. The long-term gross power price on the Nordic market is estimated at 5 ¢/kWh (eurocents per kilowatt hour). ESS is exempt from energy tax, but this would otherwise amount to 3 ¢/kWh. The average price paid for heat recovered to a district heating system in Sweden was 2 ¢/kWh. The average price of district heating to large companies in Sweden was 7 ¢/kWh. At an estimated COP for a heat pump to cool at 40°C and eject heat to district heating at more than 80°C would be around 4, indicating a cost of electrical power for the process of ¼ times 5 ¢ or 1.25 ¢/kWh.

## Climate conditions in the case

The conventional cooling solution for research infrastructure facilities like the ESS is to either make use of a local body of water, if available and allowed, or to use cooling towers. Heating a local ecosystem has an associated impact on that system. Cooling towers consume electrical power and substantial amounts of water and chemicals.

A closed loop system based on heat pumps requires more energy than cooling towers, but does not consume the cooling water or the chemicals, and much of the chemical use is avoided completely as the system is not open to contamination.

Specific conditions in Sweden, compared to global averages, are that the climate is cool, so that heating is required for most of the year, whereas cooling is not in great demand, and that the supply of fresh water is ample.

## Collaboration and comparison with other facilities

A study conducted within the EU-sponsored EuCARD2 (Grant Agreement 312453) project for accelerator development examines 12 large-scale research facilities (Research Infrastructure), of which 10 were in operation and two in construction. The average annual energy consumption for the facilities (including estimates for the two in construction) was 180 GWh per year, with considerable variation in the group. Discounting the outlier in each end, the average fell to somewhat under 100 GWh. The cooling requirement varied from 40% to 60% of the electricity use. Cooling at operating facilities was at low temperature (up to approximately 40°C). The facilities in construction had included a high-temperature (up to approximately 80°C) cooling loop for part of the cooling demand [38].

The study examines a number of technologies for reuse of surplus heat, divided into high-temperature technologies, meaning those requiring 80°C or more, and low-temperature technologies. The high-temperature technologies examined were district heating, heat-driven cooling, and power production using the organic Rankine cycle (ORC). Both the heat-driven cooling technologies examined and the ORC required cooling to function and thereby produced a flow of lower temperature heat. These options were therefore only of interest for facilities with a low-temperature heat sink available. District heating, on the other hand, was only of interest for facilities located close to a significant heat demand, preferably with an existing infrastructure for distribution.

The low-temperature option studies included low-temperature district heating, heat storage, food/fodder production, biological/chemical purification/separation techniques, wastewater treatment, and ground heating (e.g., for ice and snow removal).

The EuCARD2 project involves 40 partners from 15 European countries. The energy efficiency effort within this collaboration stems from "the need to increase the efficiency of energy use during operation for cost and sustainability reasons is common in all accelerator facilities in research and industry" [39]. Another European collaboration within a similar area is the workshop series "Energy for Sustainable Science at Research Infrastructure" hosted by CERN, ESS, and ERF (European Association of National Research Facilities) (https://indico.cern.ch/event/245432/, http://europeanspallationsource.se/energy-workshop). After the first workshop, the hosts published an executive summary highlighting the value for society of the efforts at research infrastructure in energy and sustainability management. The value was created first by the direct effects in energy efficiency at the facilities, but potentially more important effects could be created by using research infrastructure as innovation hubs, testing grounds, and training grounds, roles that research infrastructure is created to fulfill [40].

## Proposal: waste heat for food production with a nutrient loop

Based on the estimated heat flows at various temperatures, the value of heat sold for district heating purposes, and the estimated cost of electricity to drive the heat pumps, the estimated value of heat at the different temperature levels can be derived. This varies over the year with the value of the heat and electricity prices and may be a positive or negative value. These calculations form an economic basis for the development of alternative uses of waste heat.

The first such use to be developed in the case was for onsite space-heating needs. Space heating can easily be achieved in buildings so designed with water temperatures of 40°C. ESS has developed an internal heat distribution network with a supply temperature of 55°C and return 25°C. The annual heat use was estimated at 5 GWh. The remaining heat would therefore amount to 265 GWh.

Since existing demand required heat pumps to augment temperature, and internal demand was limited, ESS sought opportunities to create new demand, by offering the heat to users that would establish nearby specifically to utilize the offered heat. This was done in an open call for proposals published on 10 of September 2013.

Biological systems offer an opportunity to make use of heat. Fish, plants, algae all have in common that, within limits, growth is stimulated by an increase in temperature. As one example, an increase in temperature from 8.6°C to 13.7°C has been shown in a specialized research facility to double the growth rate in salmon smolt [29].

An existing use of surplus heat for biological systems exists only 125 km northeast of ESS, at the Elleholm greenhouse facility, which at 8000 $m^2$ greenhouse area is Sweden's second largest producer of tomatoes. Elleholm uses waste heat from nearby Södra Cell, a pulp and paper plant.

The details of the Elleholm case differ from ESS, in that the supplying facility at all times has a significant

**Table 2.** Identified uses for excess heat under 60°C in a cooling chain from heat to food.

| Temperature (°C) | Food and fodder production process |
|---|---|
| 40–60 | Low-temperature drying |
| 32–40 | Fermentation of microbes (yeast, bacteria, microalgae) |
| 22–32 | Warm water fish farming (tilapia, shrimp, perch, turbot) |
| 18–22 | Green house hydroponics (tomatoes, cucumbers) |
| 10–18 | Cold water fish farming (salmonids, white fish, sturgeon, crayfish) |

excess of heat of prime district heating temperature. There is therefore no incentive to explore low-temperature heating systems. Despite this, the Elleholm management has estimated minimum temperature needed at 38°C.

In collaboration with the Swedish University of Agricultural Sciences, SLU, and based on the results of the abovementioned open call, ESS has identified a number of potential biological uses of its excess heat, shown in Table 2.

A vital aspect of the SLU-ESS proposal is that the components of the cooling chain also could be linked in a nutrient chain. The heat recycling at the Elleholm facility is a significant gain in sustainability, but the facility still uses commercial fossil fertilizer, which represents a significant indirect energy use. If a greenhouse facility were colocated with fish farming, the fish excrements could be directly used as fertilizer in a hydroponic system. Fish fodder could be made from yeast, based on a substrate of food waste and agricultural waste (including plant waste from the greenhouses). This would require a drying process to create fodder, which could also be achieved with low-grade waste heat.

A graphic of the SLU-ESS initial proposal taken from the ESS Energy Design Report [41] is shown in Figure 1.

# Analysis

## Generality of the case

The case of the European Spallation Source shows an example of the phenomenon that surplus heat has become an economic and environmental cost. The cost is first, a direct cost for operating cooling systems, and second, the cost of a lost opportunity, and third a presently undefined cost for the ecosystem in coping with an increased ambient temperature due to the release of large volumes of cooling water. The case thus shows some characteristics that may be common to energy-intensive activities, these being that (i) large quantities of excess heat are produced, (ii) well-managed, the heat can be conserved at a temperature that can be useful for heat and biological processes, and (iii) conventional management of this resource represents a cost burden to the organization. In EU it is estimated that this low-temperature heat loss equals 500 billion Euro in petrol equivalents [25].

## Identification and interaction of relevant physical systems

In the case, a hierarchy of energy forms was established by the relative prices of heat and electricity, and the electricity demand for heat pumps to supply appropriate temperatures. The electrical power system represented the

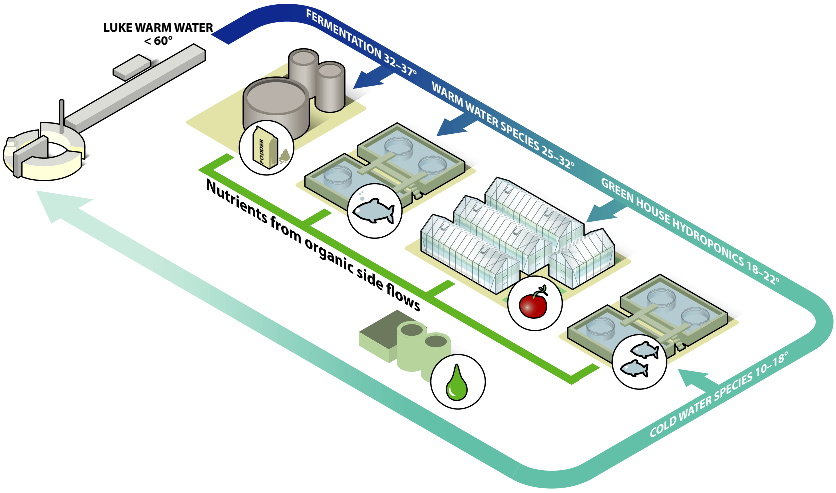

**Figure 1.** UNCSD theme indicator framework [15].

highest value systems, and cooling systems of various temperatures represented falling value with temperature level. This is a hierarchy of monetary value, but the same outcome would result from an analysis based on the second law of thermodynamics. The theoretical limits in Carnot cycle conversions function can be used to assign relative values to heat of various temperatures compared to electrical power [42].

A low-temperature heat-recycling scheme is therefore also a low-value scheme. This can enable uses that require only low-grade heat, but are not competitive if they must purchase heat at the high-value price.

## Food is energy

Agriculture plants convert solar energy into energy for human consumption in the form of food. However, modern agriculture methods depend heavily on fossil fuels. Fertilizer represents a significant, indirect part of energy consumption for food production. For example, in Europe, farmers use about 10.5 million tons of nitrogen fertilizer 2010 and the trend is an increase. Phosphate fertilizer 2011/2012 was 23 million tons. Of this, EU imports roughly 25% (IFA, Fertilizer Europe.Com, 2014). The energy consumption to produce fertilizer varies considerably with the fertilizer type; nitrogen fertilizer requires much more than phosphorus or potash, but in order of magnitude this may represent an energy consumption of 100–150 TWh, or an eighth of a PWh. On the other hand, mining of organically available phosphorus, besides fossil fuels, do include a fraction of heavy metals, especially cadmium and aluminum, adding to its environmental load [43]. The total electrical consumption of Sweden in 2012 was 142 TWh; replacing mineral fertilizer is therefore a significant energy efficiency gain for agriculture.

## Peak oil use, peak land, and peak fisheries

The term “peak oil” is used to describe a moment when the supply of oil would begin to decline, and when that might happen has been periodically much debated. More recently, “peak oil consumption” is being discussed, meaning the event that oil consumption would begin to decline.

It is clear that the event “peak arable land” has repercussions for future food supply. This moment might already have past. Loss of arable land is caused by degradation, and by constraints imposed by climatic, environmental, and human activity. The United Nations’ Food and Agricultural Organization (FAO) track land degradation and publish a “Global Land Assessment of Degradation.” If indeed “peak arable land” has been passed, it follows that all increased food production must come from greater output per land unit.

Furthermore, it is clear that “peak wild fish harvest” has passed. Nearly 85% of our wild fish stocks are near, at, or over its maximum harvest [27]. Increased fish consumption must therefore come from aquaculture.

## Food and fodder

Within the world’s food production system, basic food for human consumption competes with animal feed, and to a lesser extent also for energy production. In animal feed, 47% of soy and 60% of corn produced in the United States is used and at global scale more than 40% of these crops are used for animal feed [28, 43]. In 2007, EU produced less than 1 million tons of soy per year, and imported around 25 million ton of soybean meal (EU-27) (http://www.indexmundi.com/agriculture/?country=eu&commodity=soybean-meal&graph=imports). Today, only around 6% of soybeans are eaten directly as whole beans or in products like tofu and soy sauce [44]. Approximately 75% of all produced soybean is used for animal feed [44, 45]. To produce this amount of soy almost 15 million ha of agricultural land area is needed, nearly equal the total agricultural land of Germany [45]. In fact, soy fields now cover more than 1 million square kilometers of the world – the total combined area of France, Germany, Belgium, and the Netherlands [44]. Also, approximately 80% of that soy is genetically modified [44]. Based on the present increase in animal-derived food products, FAO [28] estimates that world soy production will double to 2050. Ever since soy production began increasing in South America in the 1960s, soy has been associated with clearance of some of the world’s most crucial ecosystems, such as the Amazon and Cerrado, leading to loss of biodiversity. This loss of valuable forests and other native vegetation means that the carbon storage services they provide are lost forever, contributing to global climate change. Soy production is also linked with unsafe and excessive use of pesticides, violation of land rights, and unfair labor conditions [44]. The import of soy to EU has remained more or less stable over the last 15 years (EU-27) (http://www.indexmundi.com/agriculture/?country=eu&commodity=soybean-meal&graph=imports). In addition to plant-based nutrients, about a quarter of world catch of fish is used as animal feed [27] underlining the enormous amount of high-quality nutrients of human food quality presently used in animal feeds.

Horticulture is water intensive; the plants consume water and much is also lost in evaporation, one of the issues driving the idea of closed greenhouses. In the case, water usage was seen as an important sustainability advantage for location of greenhouses in Sweden, as the supply of fresh water is ample and the cost of often negligible. The cool climate and the resulting need for heat in greenhouses was a competitive disadvantage, to the extent that Sweden's horticulture industry was in a steady state of decline. Only 10% of tomatoes in Sweden are produced domestically [46]. An inexpensive, sustainable heat source would therefore potentially shift greenhouse production to a place with an abundance of water and thereby lessen the pressure on scarce resources elsewhere.

The indicative prices uncovered show that value of cutting out the middle man in the district heating system and establishing a direct relationship between the waste heat producer and the consumer was as much as 5 ¢/kWh. Additionally, a supply and demand at 40°C rather than 80°C would mean a savings of 1.25 ¢/kWh. With a total heat supply of 250 GWh per year, this would mean a total added value of 16 million Euros a year, quite likely enough to negate the competitive disadvantage of the heating need in Sweden.

## Microbes and the protein chain

In cells, RNA relays the information of DNA to the protein synthesis. Microbes have high levels of RNA (10–15%) because of the high level of protein synthesis. Living cells metabolize the N (nucleotides) in RNA to uric acid. In mammals uric acid leads to kidney stones and gout [47]. Fish, however, have retained their ability to eat microbes and have no problem with uric acid [47–50]. Using microbes to produce fish fodder offers an opportunity to profitably use the fantastic growth rates of microbes. Microalgae tend to multiply at a rate of once per day, that is, a daily rate of $2^1$. Yeast doubles every 2 h, that is, $2^{12}$, whereas, for example, *Escherichia coli* bacteria the pace is as high as every 20 min during the exponential growth phase, leading to a daily rate of $2^{72}$.

Taking the example of yeast, a study at Swedish yeast factory demonstrated a in favorable conditions a start culture of 10 mg of yeast developing into 150 tons in a week given free access to short carbon chains and ample supply of minerals.

Protein is important because around 40% of fish fodder is protein, in the average (tilapia/carp 30%, marine species 50%, salmon 40%). Table 3, below, details some of the main similarities and differences between protein chains for food production based on soy compared with yeast. For fodder production using yeast, the dominant energy use is for the drying process.

**Table 3.** Protein chain comparison with energy use.

| Protein chain | Soy | Yeast |
|---|---|---|
| Product | Soy meal | Protein meal |
| Protein content | 50% dry matter | 50% dry matter |
| Suitability | Terrestrial farmed animal[1] and humans | Fish and shrimp[2] |
| Main energy use | Farm/harvest, processing, transport | Drying |
| Energy use, kWh/kg | 2.8 | 1.46 |
| Energy supply | Fossil based | Surplus low-grade heat |

[1] Not suitable for most fish, but if used to fish needs further processing into soy concentrate which require further energy in alcohol extraction and heat treatment to reduce antinutrient and endothelial inflammatory factors. In this process protein is concentrated from under 50% dry matter to over 65% demanding a parallel increase in amount of soy bean raw material per kg of concentrate, that is, in production energy.
[2] Suitable for monogastric terrestrial farmed animals at low inclusion level.

## Creation of new dependency

From a systemic view, recycling is usually seen as an inferior option to prevention. This is also the case in the ESS program, where the "Responsible" goal of energy efficiency was the superior goal. A related issue is the question of whether heat recycling might cause a dependency on a fossil-based and/or wasteful process. For example, in this case, further efficiency gains were envisioned in the accelerator.

In comparison, heat recovery from incineration of waste streams or from electrical power production from fossil fuel sources may be seen as an unsustainable subsidy to these practices and as a risk if the heat source should cease.

In this case, ESS, backed by 17 democratic governments and a major potential source of new knowledge enabling new sustainability solutions, may be seen as a sustainable activity in its own right. The explicitly planned life span of 40 years also adds a measure of certainty of supply.

More generally, source dependency is lessened by lower temperature level. This is because the lower the temperatures, the more easily the heat source can be replaced by solar or geothermal heat. Therefore, heat recycling at low temperature can be seen as an enabler for restructuring of the energy system.

## Sustainability assessment

The UNSCD sustainability framework [15] is shown in Figure 2. The framework is established for indicators on for a nation or region, not for a specific technology. It is chosen here as a reflection of a consensus view of the main international sustainability challenges.

In the CSD framework, the Health theme includes the subtheme Drinking Water. Climate Change is a subtheme of Atmosphere. Agriculture is a subtheme of Land and includes the indicators Arable and Permanent Crop Land Area and Use of Fertilizers. Oceans, Seas, and Coasts

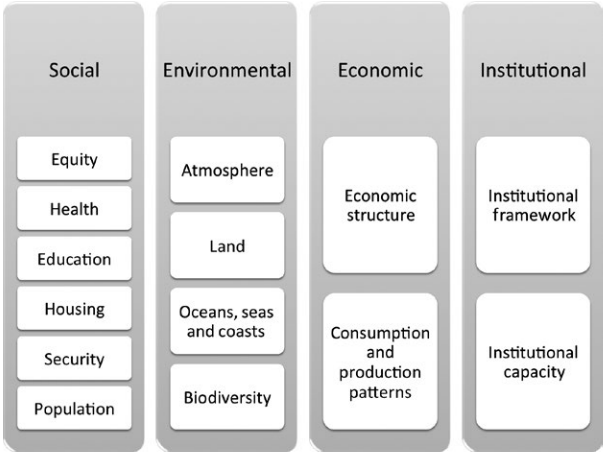

**Figure 2.** The proposed cooling chain for ESS with food and fuel production (*source*: [41]).

include issues of the impacts of nutrient flows into bodies of water as well as fishing yields. Among the Economic themes, Energy Use is a subtheme of Consumption and Production Patterns as is Waste Generation and Management, which includes the indicator Waste Recycling and Reuse.

The following themes, subthemes, and indicators are therefore relevant as categories of analysis to the case: groundwater and coastal waters; fishing, arable, and permanent crop land area; use of fertilizers; energy use; climate change; and waste recycling and reuse. The Institutional themes are specific to the national or regional level, and not applicable to a specific technology.

To ensure relevancy, a comparison was made with an assessment method developed specifically for energy [51]. As a result, four additional categories were added: resource depletion, cost/benefit, security and diversity of supply, and public acceptability. A summary of the assessments according to these categories is shown in Table 4.

The positive climate effect of replacing red meat with fish has been quantified in studies. At global level, meat production accounts for 18% of released climate gases [27, 28]. Gonzales et al. [52] in parity with Pelletier and Tyedemers [53] show a much lower energy use and release of $CO_2$ equivalents in producing 1 kg fish compared to red meat. Naturally this varies with species and production system. For example, Troell et al. [54], Tyedemers et al. [55], and Pelletier and Tyedemers [53] showed that cultured carp yielded an "industrial energy" return in edible food of 94%, while fishery harvested fish reached 8% and farmed salmon using fabricated diet based on fish and plant protein meals varied between 8% and 17% pending conventional or organic sources, while feed lot beef reached 2.5%. The differences mainly lie in the feed compartment. In these studies, the origin of the energy was not considered.

The increased predictability of supply from land-based fish farms is because unpredictable factors such as weather, diseases, etc., will be possible to control to a much higher extent in a closed system.

## Main Conclusions

In this case, the value of energy quality is demonstrated. The preservation of temperature in cooling system was

**Table 4.** Summary of sustainability assessment by category.

| Theme | +/– | Motivation |
|---|---|---|
| Groundwater and coastal waters | + | On-land closed-system fish farms can materially reduce the impact on inland and coastal waters from open-water fish farms. |
| Fishing | + | On-land aquaculture has the potential to alleviate pressure on wild stocks, allowing these to recover. |
| Arable and permanent crop land area | + | The production from greenhouses is 40–80 times higher (in monetary value) than from farmland per unit area. |
| Use of fertilizers | | By combining the appropriate amount of fish farming with horticulture, nutrient flows from fish excrements can replace commercial fertilizer in greenhouses, provided the feed is based on nonplant materials. |
| Energy use | + | Use of waste heat for greenhouses and land-based fish farms can substantially reduce their energy use. |
| Climate change | + | A positive climate change effect comes from reduced energy use, reduced fertilizer use, and a replacement of red meat by fish due to avoided methane release and great energy efficiency. |
| Waste recycling and reuse | + | Waste nutrient streams are proposed as a basis for producing fish fodder. If implemented, this would be a significant valorization of a waste stream. However, technical hurdles remain. |
| Resource depletion | + | Fossil fuel, fresh/ground water, and fossil nutrient use is reduced. |
| Security and diversity of supply | + | The diversity of energy supply would increase. Heat storage capacity would be necessary and could contribute to stability. Diversity and predictability of food supply would increase. |
| Public acceptability | – | Industrial-scale fish and greenhouse farming may be considered unsightly. Light pollution may be an issue. Traditional farming and fishing is culturally ingrained. Animal feed based on recycled nutrients need strict food security control. |

shown to add significant value. Conversely, using as low quality as possible can significantly lower costs. The indicative figures provided in the case, for example, 40°C for heating, 60°C for cooling data centers, and 70–80°C for cooling power electronics corroborate some earlier research. With additional verification, these benchmarks could inform future energy performance efforts.

Heat recycling was shown to be a considerable enabler for food production. The analysis indicates that waste heat resources available that are comparable to those in the case are abundant. If these can be combined with waste nutrient streams and converted to food and energy, there is potential for noticeable impact on global food supply. Additionally, if the efforts to integrate nutrient and cooling chains are successful, a large-scale rollout of this technology could supplant substantial amounts of fossil fertilizer and thus significantly lower the environmental impact of food supply.

Making use of low-grade heat in biological systems may also enable future development by lowering the threshold for renewable heat sources such as solar and geothermal.

The study is limited to a single case, and although the studied case organization is well established, the energy processes described are still being designed and will not be observable for some years. Further studies are therefore urgently needed, particularly studies of real energy flows and demonstration facilities for food production.

## Conflict of Interest

None declared.

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