Hi-SCALE

CA19108 High-Temperature SuperConductivity for AcceLerating the Energy Transition

Deliverable D4.1: Mapping report on materials, applications, techno-economics and environmental aspects of HTS

This COST aims to analyse High-temperature superconducting (HTS) materials by a systemic approach that will create the path **from materials to devices**; foster **improved modelling and advanced computation** paradigms; provide methodologies and demonstrators for addressing **industrial challenges and applications**; and develop tools for the **economic and sustainability assessment** of HTS technologies.

The WG 4 aims to identify gaps related to HTS **cost efficiencies, environmental impacts and applicability** that hinder a broad market penetration of these technologies. A major challenge is how to **evaluate and demonstrate the system benefits of HTS**, and how these may be economic and environmentally valued.

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Abbreviations

HTS	High-Temperature Superconductor / Superconducting
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory (Analysis)
LCIA	Life Cycle Impact Assessment
UNEP	United Nations Environment Programme
WG	Working Group

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1 Introduction

EU has committed to reducing its greenhouse gas (GHG) emissions by at least 55% by 2030 compared with 1990 levels and becoming the first carbon neutral continent by 2050. Considerable R&D effort is still needed to electrify transportation, improve storage technologies and smart power grids, to integrate high shares of intermittent renewable energy supply and increasing electricity demand, in an affordable, efficient and secure energy system[1], [2]. This will create new opportunities for innovation as set in the EU Green Deal. The challenges addressed by Hi-SCALE are thus fully relevant and the timeliness of the Action is duly justified by above challenges [3].

As any new technologies, large-scale High Temperature Superconducting (HTS) applications face challenges related to cost, efficiency, environmental impact and applicability that hinder their broad market penetration. It is thus crucial to study the life-cycle system effects of HTS technologies. This entails how HTS systems may be economically and environmentally competitive vis à vis conventional solutions, considering the energy and resources consumption, emissions and costs over their entire life cycle. It is essential to have a systemic vision that requires a highly interdisciplinary approach.

1.1 The working group 4

The Working Group 4 focuses on the economic and environmental sustainability aspects related to HTS technologies by the collection and provision of available techno-economic and LCA analysis studies. The aim is to support demonstrating the potential positive externalities and long-term gains achieved with HTS technologies and the identification of opportunities, challenges and gaps related to sustainability. Doing so can help to address named gaps in future or ongoing research and serve as a starting point of the same.

1.2 Tasks of WG 4

The following tasks have been formulated to achieve the before mentioned goals over the time frame of four years:

T4.1: First screening of applications in line with T3.2 of WG3. The screening will be performed via input of the other WGs. Also, distinct criteria namely the technical, environmental and economic aspects are identified for selected applications and related superconductor technologies (material to system level). The screening will enable a purpose driven discussion and shall serve as starting point for further works in the field of techno-economics and sustainability assessment.

T4.2: Conduct exploratory review of relevant superconductor materials, devices and systems regarding their environmental and techno-economic performance and potential application and compare it with conventional competing solutions.

T4.3: Carry out Workshops, presenting e.g., screening results based on existing works, providing an initial input to the other WGs. A second one will run at the end of Hi-SCALE to present explorative results associated with a certain application field.

T4.4: Identify what is required to enhance further sustainability assessment on different TRL and technology levels (materials to system level) to provide input for future assessment. This includes already a screening of applications but allows u to open for further research and to connect to other groups.

1.3 Deliverables

Following deliverables have been formulated to fulfil the before mentioned tasks:

D4.1 Mapping report of the field, data gaps, what is needed, main applications, main materials (related to techno-economics and environmental aspects). 1Y Q4

D4.2 Provide a workshop report for the activities defined in T 4.3 3Y Q1

D4.3 Working paper on techno-economic and environmental aspects of superconductors starting from materials to applications to system perspective (→ building up on 4.1) 4Y Q 3. Inputs collected over the time of the COST action to provide a starting point for further assessments that can serve as a blueprint for assessment of HTS.

This report is realized in frame of D4.1. Mapping report of the field, data gaps, applications, and main materials. Also, a brief introduction to the field of sustainability and methods used for techno-economic evaluations and life cycle assessment to provide a better understanding of related challenge.

The structure is organized as follows; first a general overview of life cycle thinking including an introduction on major techno-economic evaluation methods and life cycle assessment. It aims to communicate in a fast way the basics of these methods, so that they can be applied in corresponding assessment. Then the mapping of the HTS field is carried out to gather an overview of the activities carried out within the cost action and beyond. Then a comprehensive literature review is carried out to identify gaps in the area of sustainability and techno-economics.

2 Sustainability assessment challenges

The estimation of the sustainability potentials is often named as a major goal in literature or policy documents when it comes to the selection or development of a technology as e.g., HTS technology. The concept of sustainable development (orientation towards efficiency gains and improvements of technology) and sustainability (perspective on related to individual values and attitudes towards nature) has been object of interest in a wide spread of literature [4], [5], [6], [7] and [8].

The concept of sustainability itself was first formulated in the Brundtland Report "*Our common future*" from 1987 [9] and defines sustainable development as follows:

> *"Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs."*

This definition inhibits on the one side aspirations between humanity towards a better life and the limitations imposed by the state of technology and social organization on the ability of nature to meet these needs on the other side [10]. Environmental concerns are essential for this view on sustainable development, but the primary argument is on welfare in the context of inter-generational equity. Sustainable development represents a particular shift in perspectives, away from a focus on purely economic development towards a more multidimensional development. The 2030 Agenda for Sustainable Development [11] adopted by all United Nations Member States in 2015, sets 17 integrated sustainable development goals (SGD) underlining the fact that development must balance social, economic and environmental criteria [11], [12]. Ensure access to affordable, reliable, sustainable and modern energy for all is defined as one of the SGD, which among other, is associated with improving energy efficiency, increase the share of renewable energy use and promote investment in energy infrastructure and clean energy technology. In line with this, the EU has the collective ability to transform its economy and society to put it on a more sustainable path [13]. This requires also approaches that enable it to identify sustainability hot spots related to the development of new technologies as HTS.

There is a high number of different methodologies available to carry out corresponding sustainability assessments. However, different methods are applied depending on the TRL. It can be a simple material screening for early TRLs to streamlined LCA for first laboratory prototypes, up to full LCAs and techno-economic analyses, for higher TRLs. The latter includes the assessment of potential use cases of the technology and their corresponding environmental and economic performances. In the following the most relevant ones for the assessment of HTS will be presented.

2.1 Life cycle thinking

Traditionally, when analysing the environmental, social or economic impacts of a product the focus lies on the production site and the manufacturing processes. However, this perspective neglects that every manufacturing process requires precursor materials or energy, which in turn also must be produced or generated. These precursor materials may also require precursors themselves, which also must be produced and so on. Manufacturing one product does not only cause impacts throughout its own production but also causes an entire supply chain of processes with each of them causing environmental, social and economic impacts as well.

This is the general idea of life cycle thinking. According to the life cycle initiative by the United Nations Environment Programme (UNEP) [14] the idea of life cycle thinking is to go “beyond the traditional focus” and “to include environmental, social and economic impacts of a product over its entire life cycle”.

Figure 1 shows a typical schematic of such a product life cycle. It begins with the raw material extraction and continues with the design and production. In comparison to traditional analysis, the life cycle also includes packaging and distribution, the use and maintenance phase, as well as the end of life. The last phase could either consist of disposal, recycling, or reuse of the product.

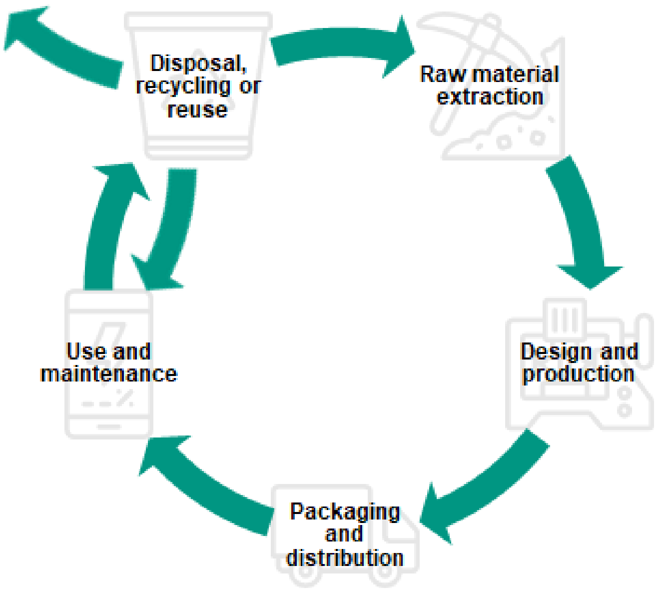

Figure 1 Typical product life cycle scheme (Source: Life Cycle Initiative)

The major step within almost all system analysis approaches is the definition of a system and its borders. A system is always in interrelation with its environment (may it be markets, nature, an electric engine or society). Over its borders, there is a continuous flow of inputs and outputs of materials, energy or economic value. This approach makes it possible to understand major interrelations within a selected system and to identify possibilities that might lead to a better system.

Tools used to do so are typically; techno-economic assessments, economic-, social- and ecological life cycle assessment, material flow analyses, ABC-Analysis, and energy system modeling, etc. [15], [16].

In particular, Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and social Life Cycle Assessment (sLCA) are methods that enable the identification and quantification of potential benefits (or disadvantages) of a new technology in comparison to traditional alternatives. All these approaches include the extraction of raw materials, production, use phase as well as the disposal or recycling of products (cradle to grave). This assessment is done by accounting for burden shifting between these life cycle phases and the tracking of impacts in diverse impact categories.

2.2 Life cycle Assessment (LCA)

Life cycle assessment is a standardized approach within DIN ISO 14040 [17] and 14044 [18] that documents a product's or product system's environmental impact over the complete life cycle. Such impact categories can range from climate change and resource use to human toxicity, acidification, and ozone depletion. It is characterized by four mandatory phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation.

- Goal & Scope Definition**:** The first step is to establish the aim of the study as well as its depth and intended application. Additionally, the product systems, their respective system boundaries, and the functional unit are defined, and the impact assessment methods are selected.
- Life Cycle Inventory Analysis (LCI): The second step covers quantitative information regarding input and output flows of all unit processes. Inputs include material and energy consumption as well as potential transformation processes or other services. Outputs include the reference flow, waste flows, emissions and potential by-products.
- Life Cycle Impact Assessment (LCIA): Within the third step, the results of the inventory analysis are translated into potential environmental, social and economic impacts using impact factors from the selected impact assessment methods. These impact factors represent the relevance of an elementary flow (e.g., methane) in a specific impact category (e.g., climate change) compared to a reference elementary flow (e.g., carbon dioxide).
- Interpretation: During the final step, important parameters such as specific life cycle phases, production processes or impact categories are identified. Additionally, the results are checked in terms of consistency, sensitivity, and uncertainty, so that in the end conclusions and recommendations can be made.

There is a set of well-known methodologies available for LCA as Eco-Indicator 99 for endpoint indicators (endpoints and single score) and CML 2002 for midpoint indicators (greenhouse gases, ozone depletion, etc.) [19]. ReCiPe is a follow-up of these two methods. It combines and harmonizes midpoint and endpoint approaches, and all impact categories have been redeveloped. ReCiPe allows users to choose their level of result through eighteen midpoint indicators which are relatively robust, but not easy to interpret. Other commonly used impact assessment methods are the International Reference Life Cycle Data System (ILCD) and its successor Environmental Footprint as well as the sum indicator Cumulative Energy Demand.

Two selected examples for LCIA categories used within ILCD, which are also used later on in the screening, are indicated below based on [20] and [21] to provide a first impression of LCA results:

- climate change indicated changes induced to the World's climate because of the emissions to the atmosphere of the so-called greenhouse gases, such as CO_2, N_2O, CH_4 and fluorinated gases (e.g. emitted from the combustion of fossil fuels or from industrial processes). Known consequences of climate change include increased global average temperatures and sudden regional climatic changes, which can directly and indirectly negatively affect the natural environment, human health and the availability of natural resources. Unit of measurement: kilogram of carbon dioxide equivalent (kg CO_2 eq).

- Resource depletion – metals, minerals, fossils fuels and renewables: There is a finite number of non-renewable resources such as metals, minerals or fossil fuels like coal, oil and gas available on earth. This impact category is that extracting a high concentration of resources today will force future generations to extract lower concentration or lower-value resources. Unit of measurement: kilogram of Antimony equivalent (kg Sb eq).

2.3 Techno economic analyses – state of the Art

In this section, a general introduction is given on techno-economics. In general, techno-economic assessments can include several methods that are used to measure technological performance and economic feasibility. The *Life Cycle Costing (LCC)* is one method that is often named in context of energy systems [22]–[24] and that includes in line with LCA all the relevant phases of a product over its lifetime. The *Levelized Cost of Electricity (LCOE),* sometimes also referred to as Levelized Cost of Energy is also widely used. It enables simple comparison among power generation technologies [25]. More recently, the *levelized Cost of Storage (LCOES or LCOS)* [26] has been used as a distinct method to compare different storage technologies. It must be mentioned that it is difficult to draw a border among these different methods as they share several elements.

2.3.1 Standards and Frameworks for techno-economics

There is no common standard for carrying out a techno-economic assessment or in particular a LCC, LCOE or LCOES. The choice of a specific method depends on the availability of data, time, resources and aim of the study. However, there are guidelines as the IEC 60300-3-3 or VDI 2884 for general application by both suppliers and customers, explaining the purpose and value of LCC and outlining the general approaches [27], [28]. There are only few differences within literature regarding the entire LCC concept, but there are variations regarding the calculation methods. A comprehensive comparison of LCC studies using different approaches is given in [23]. Note that the standards for LCA can serve as a reference regarding the overall approach (e.g. goal and scope definition, data collection, calculation of cost and finally interpretation of results) [17], [18].

In the following section, a brief overview of the main calculation methods which are applicable for LCC, LCOE or LCOES is given. These are usual traditional static and dynamic methods used for investment analysis [28].

2.3.2 Non-Discounted static methods

Non-discounted static investment analysis methods are used to compare costs and benefits that occur during one representative period. still used in industrial practice due to their relatively simple handling [29], [28]. Well-known static methods include simple cost accounting and simple cost comparison. In general, all methods observe one representative period of the total service life of a product (typically one year), and count all in and outgoing cash flows.

The cost comparison method is a simple way of comparing investment alternatives determined by fixed and variable costs where the most economical option is selected [28] [29]. A main problem of this method is that cash flows are not uniformly distributed over the life cycle of a product. Furthermore, interest and liquidity effects of deferred cash flows as well as time factors (e.g. change of the value of money or present worth factor) are completely ignored [28], [29], [30].

2.3.3 Discounted dynamic methods

Discounting dynamic investment analysis methods are used to compare costs and benefits that occur in different time periods. To do so the costs in different points over the lifetime must be converted to a common point in time to reflect the time value of money [24]. The start-up time or commissioning (Go-Live) point [30] of the assessed product or object should be taken as reference [28]. An interest rate which is based on an investors/stakeholder's time value of money perception [31] is used to discount future expenditures to present values at a certain reference time point [24]. It can be also calculated by applying the Weighted Average Cost of Capital (WACC) approach if enough information (usually very sensitive data) is available from the stakeholder. The Net Present Value (NPV) method represents the basic principle for modern investment analysis [30] to investigate the present worth of all future present values. A different form of the NPV is the annuity method []. The NPV is distributed in yearly equivalent series of cash flows over the entire lifetime of the product. Another relevant method is the Internal Rate of Return (IRR) which is used to investigate the cost effectiveness of a potential investment. The investment can be considered attractive if the calculated interest is higher than the expected Minimal Acceptable Rate of Return (MARR) or than the depreciation rate. The method can be considered as supplement to the dynamic methods applied for LCC as annuity or NPV. IRR can be estimated by iterative approximation or more easily with rough arithmetical approximation methods as simple linear interpolation between a negative and positive NPV. In general, all mentioned static as well as dynamic methods can be used for a LCC. More information about the presented methods is given in [30], [9], [24] and [31].

2.3.4 Life Cycle Costing (LCC)

LCC is used by companies for inter alia major investment decision processes, alternative production processes, maintenance and logistic concepts [28] and to identify potential cost optimizations during a life cycle. It can be also considered as an application of life cycle thinking in management and science towards sustainable production and consumption by covering, assessing and aggregating all costs in all steps during the lifetime of a product [32] as depicted in Figure 2.

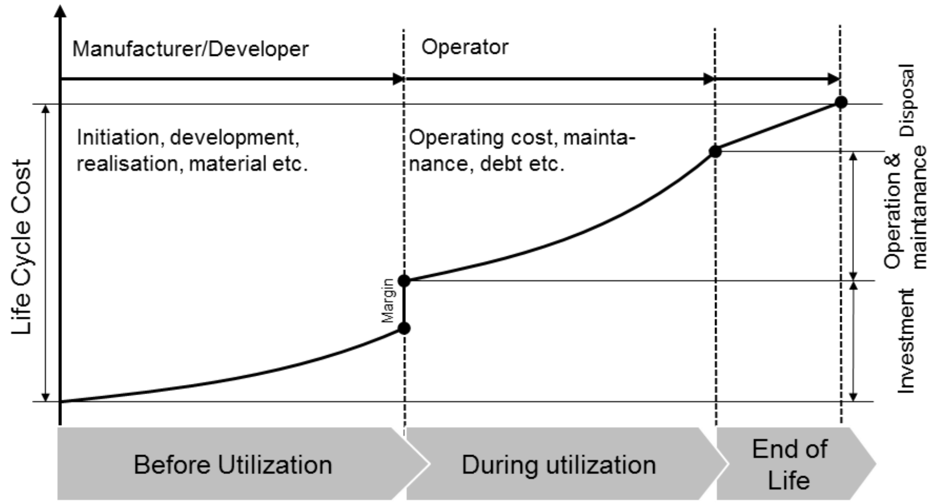

Figure 2: Scheme of cumulated Life Cycle Costs (own figure based on [28])

The costs of each life cycle stage are discounted and summed to obtain the life cycle cost [27],

$$LCC = C_{RD} + C_M + C_{OM} + C_{EOL} \quad \text{Eq. 1}$$

where C_{RD} is the discounted research and development (R&D) cost, C_M is the discounted manufacturing cost, C_{OM} is the discounted operation and maintenance cost, and C_{EOL} is the discounted end of life cost. The cost for each stage can be further divided (e.g. C_M could be divided into material cost and labour cost). A LCC can cover the entire or only parts of a products life cycle. LCC is often applied in the product's early design phase, before it enters markets [27]. Indeed, experience has shown that up to 50 % of LCC are determined by decisions at the end of the R&D phase [27].

2.3.5 Levelized Cost of Electricity or Storage (LCOE and LCOS)

The Levelized Cost of Electricity (LCOE) is one of the most used economic indicators to compare the cost of electricity generation. The LCOE is usually expressed in €/MWh [33]. The costs usually account for the same phases as for the LLC: R&D, manufacturing, operation and maintenance and end of life. Usually, discounted dynamic methods are used to obtain the discounted costs. The LCOE can be computed with the following formula:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEP_{net,t}}{(1+r)^t}}$$

where $CAPEX_t$ is the capital expenses in year t [€], $OPEX_t$ is the operating expenses in year t [€], $AEP_{net,t}$ is the net annual energy production in year t [MWh], r is the discount rate and n the installation lifetime [years].

LCOE is a useful tool allowing an objective comparison of various technologies with different capital costs, O&M costs, useful life, capacity factors, etc. The LCOE of a specific technology also measures the price at which electricity must be generated to recover all the expenses over the lifetime of the project provide information about the minimum electricity price that must be earned to become economically feasible. LCOEs should be used as a relative scale to compare various technologies, rather than an absolute measure informing investment decisions.

The Levelized Cost of Energy Storage (LCOES) is similar to the LCOE, but it refers to the cost of storing energy. The LCOES is usually expressed in €/kWh. It considers the amount of energy that can be stored and provided by a system including the losses occurring during the intermediate energy conversion steps. This power constraint effectively determines the average duration of the storage system, that is, the average amount of energy that can be stored per kilowatt of power capacity. The resulting LCOS represent the minimum price required on average per kWh of electricity stored and subsequently dispatched in order to break even of realized investments [34].

2.4 Data for life cycle analysis and techno-economics

The collection of reliable data regarding costs, technology performance, and material and energy flows is a crucial step, when performing an LCA or any techno-economic assessment.

For each unit process, a function must be identified, and a quantitative reference flow must be selected (Figure 3). For example, the function of the production of HTS tapes is to produce a specific amount of HTS tape. However, the reference flow must be chosen carefully. Using the example of the HTS tape production, potential reference flows could be the length of the tape ("1 meter of HTS tape") or the mass of the tape ("1 kg of HTS tape"). Depending on which reference flow is chosen, all input and output flows as well as monetary data must be scaled accordingly.

Therefore, each unit process, that means every individual step in the production chain, consists of the following components:

- Reference flow: The main product of the process
- Technosphere outputs: Potential by-products that can be used for other industrial processes and waste products that require waste treatment
- Technosphere inputs: Precursor materials, energy as well as potential services such as transport or transformation processes.
- Biosphere inputs: Raw materials from ground, water, or air
- Biosphere outputs: Emissions to ground, water, or air

Once the unit process has been identified, several questions should be asked during the Life Cycle Inventory Analysis for LCA. For the unit process:

- What (raw) materials and which quantity are needed?
- What are the services required?
- How much energy is consumed?
- What are the resources (input flows)?
- What are the emissions (output flows) (including during the extraction of the raw materials needed, transports and HTS waste treatment)?
- How much waste is produced?
- Are there any by-products?

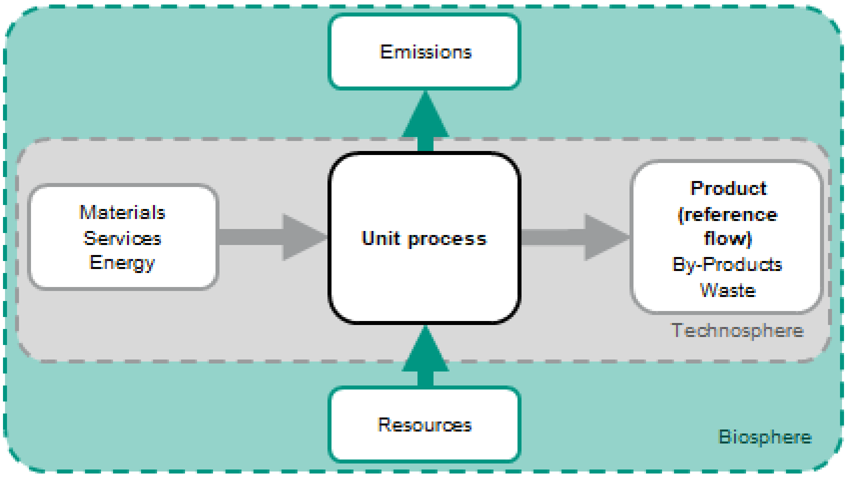

Figure 3 Simplified scheme of a unit process in a frame of life cycle assessment.

Most of these questions apply also for a techno-economic assessment, but the data to be collected are related to financial aspects: inter alia operational life, annual maintenance cost, installation costs, energy costs, replacement costs, efficiency grades, and material as well as production costs [23]. The quality, amount and other characteristics of the available data define the models and methods that can be applied and hence the results that can be achieved. This makes techno-economic assessment a strongly data driven process [35]. In general, information about the assessed technology can be derived directly from manufacturers and literature. In most cases, costs for emerging technologies have a very dynamic character, meaning that datasets should be always as new as possible. Helpful information on cost factors and standardized data can be gathered from VDI 2885 [36].

Application fields and operating conditions

In general, up-front capital and production efforts are only a part of a products life cycle. An important part is the use and maintenance phase (Figure 1) that strongly depends on both the application field and operation conditions. It has a strong influence on necessary maintenance efforts, potential replacement investments and process efficiency. Thus, the operating conditions impact both the LCC and the LCA. It is therefore necessary to clearly define the field and conditions under which the product will be operated. Additional involvement of stakeholders may help to define realistic application scenarios.

3 Mapping the field for HTS: materials, applications, life cycle assessment and techno-economics

According to literature, the properties of HTS materials related to electrical systems are high efficiency performance and high throughput with low-electrical losses. In any case, cryogenic cooling and precision materials manufacture is required. To achieve this goal, cost reductions without significant performance loss are being achieved through the advanced design and development of HTS wires, cables and magnets, along with improvements in manufacturing methods [37]. The specific challenges facing HTS materials are short piece lengths, limited production capacity, few customisation options, and high costs. Regarding cables and magnets, the challenges are the integration of the HTS (considering the brittle nature of the ceramic) and the high aspect ratio (in the case of tapes) [2].

A survey was carried among COST action to assess the current situation and future development of superconductors in terms of the state of the science related to:

- materials used
- potential applications
- techno-economic
- ecological aspects

Related gaps are identified to develop further steps necessary to close any knowledge gaps. Survey results are then contrasted and supported by the results of a comprehensive literature review of the field.

The survey is based on the activities carried in cooperation with WG 3 during the WG3/WG4 Workshop in Gliwice Poland in line with the 19th IEEE-PEMC and has been developed in close exchange with WG3 members. The online survey was carried out via SoSci Survey, a free access platform for surveys and was available for 2 months.

The survey was distributed among the working groups of the cost action and relevant other groups (companies, other academic institutions) via email. A distinction was made between industry, university / academia, research institutions and others (not classified). In total 25 persons responded to the survey (Figure 4). It should be noted that the results are rather indicative due to their very qualitative characteristics (comparable low number of participants).

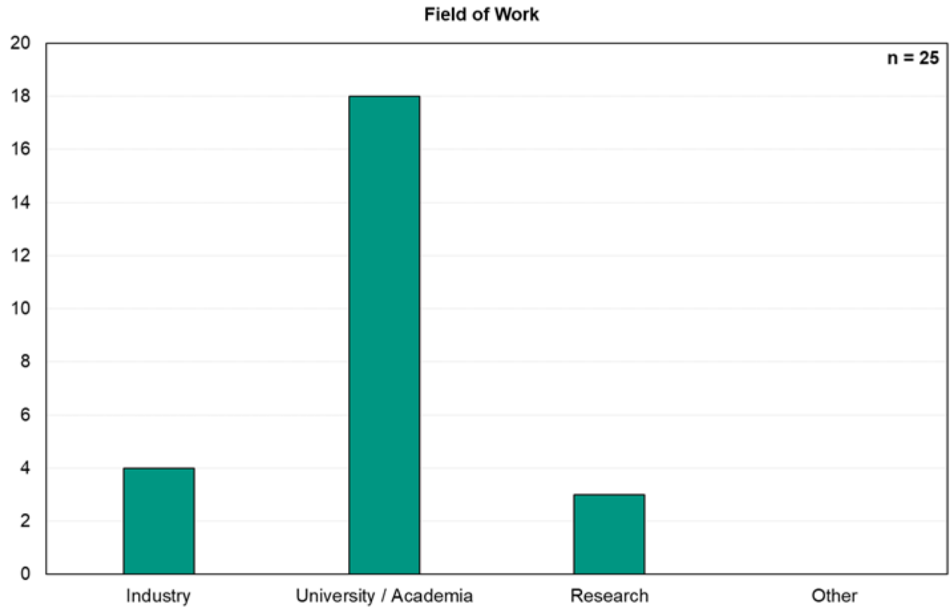

Figure 4: Affiliation of participants.

It was also of major interest to identify where the main research is being carried out (Figure 5). Here the following classification has been carried out:

- Production and development related to HTS
- Application and system integration of HTS
- Components for HTS as e.g., cooling, insulation etc.

Most participants are working in the field of application and system integration of HTS. There is a large gap of participants from the production and development segment. This represents a gap in the current state of inquiry and should be mitigated in a later stage of the COST action, when more members from the corresponding fields have joined the activity.

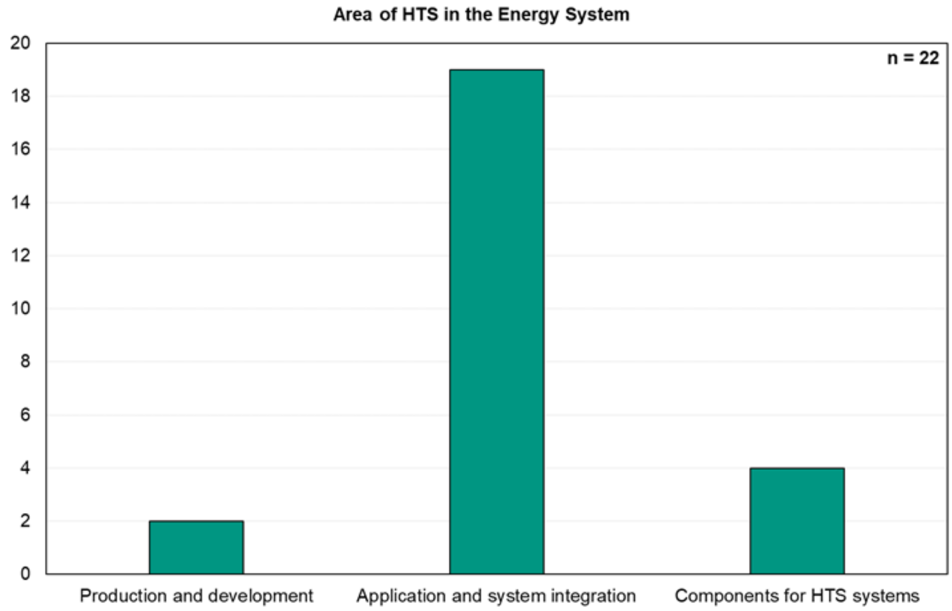

Figure 5: Overview of work field of participants.

3.1 Superconducting Materials

There are several superconducting materials available that are under research which vary according to their constituents and structures. It is possible to characterize materials into Low- or High-Temperature (HTS and LTS) Superconductors. The difference is based on the critical temperature below or above 30 K, which is the value that corresponds to the transition temperature of the Ba-La-Cu-O system, which is the first HTS discovered by J.G. Bednorz and K.A Müller in 1986 [38]. Increasing the temperature has a significant impact on overall cost, energy demand and environmental impact. However, corresponding to COST action members mainly on BSCCO, REBCO, MgB_2 as well Fe-Based HTS are the most relevant HTS materials and will be presented briefly in the following section.

Screening the HTS literature unveiled that there are mainly three HTS compounds with sufficient performance (electrical and mechanical) have found application in industrial production: $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi2223), $Bi_2Sr_2CaCu_2O_x$ (Bi2212) (summarized as BSCCO), and REBCO. They share some common properties as they all are ceramic, composed of plate-like crystals, and are formed during a high temperature heat treatment. Additionally, the oxygen content in the ceramic should be carefully controlled to obtain optimal superconducting properties. Ag and its alloys are chemically compatible and transparent to oxygen and are thus the preferred materials for HTS wire and tape fabrication. [2]

Also, MgB2 is reported to be a promising HTS material, with a lower critical temperature than those for High other Temperature Superconducting (HTS) materials (39K). One major advantage is the low cost and wide availability of used raw materials. The use of MgB_2 is rather limited to lower magnetic fields and temperatures. [39] Iron based superconductors (IBSCs) were discovered in 2006 [40] which spurred massive research effort in the area including around 1000 different materials [41]

The participants of the survey were asked to indicate the type of HTS which they are focussing on, based on the classification provided before. REBCO and MgB_2 are the most investigated types in frame of the COST action (See Figure 6), which is also in line with current literature in which these types are considered as the most promising HTS.

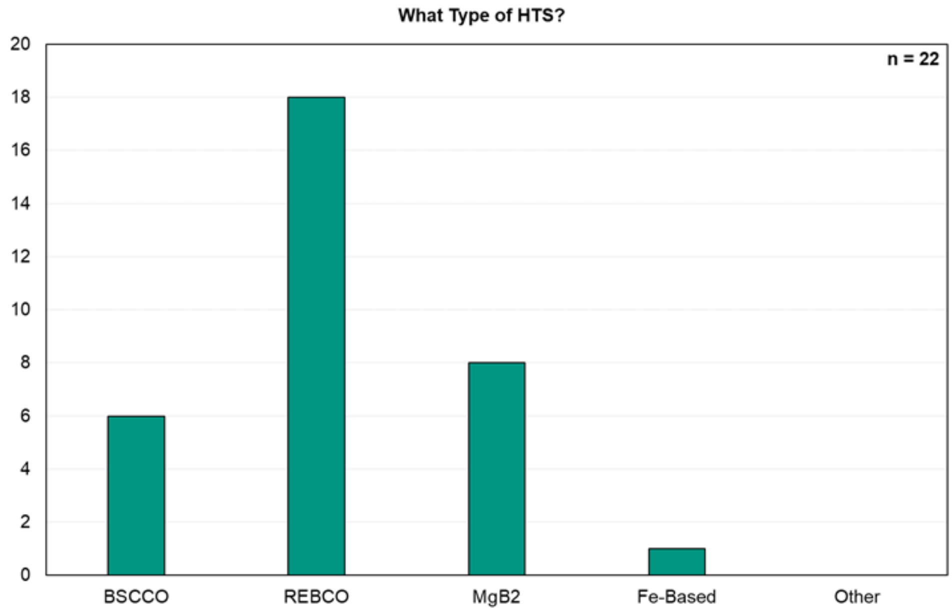

Figure 6: Overview of currently investigated HTS types of 22 participants

Participants were asked to rate the importance of the considered HTS types for future research (see Figure 7). Accordingly, REBCO and MgB_2 are also considered to remain the most important HTS Type. However, Fe-based HTS are considered to become more relevant in the future which is in sharp contrast to the current state of research indicated in Figure 7. This could be reasoned due to the high number of ongoing activities related to Fe-Based HTS [41].

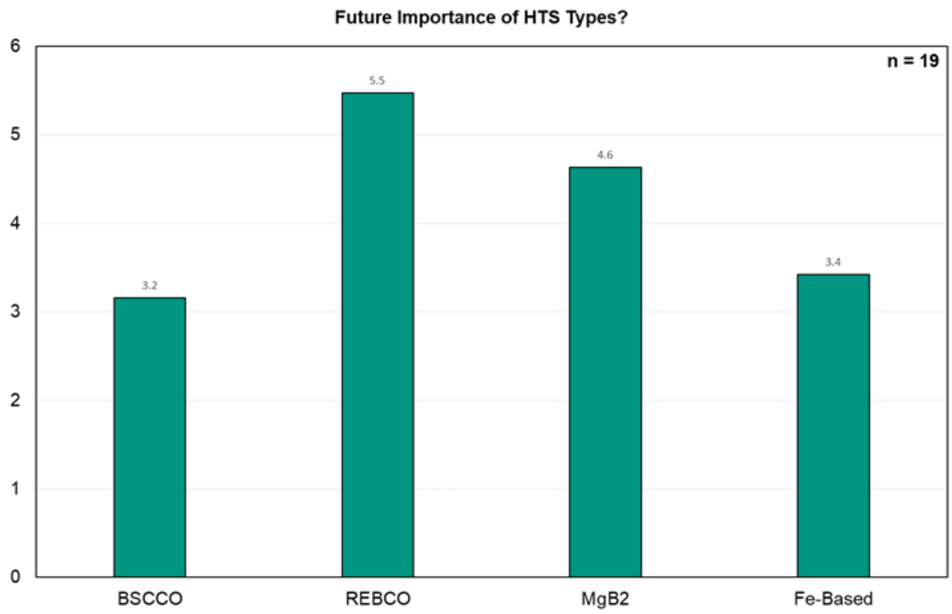

Figure 7: Expected importance of different HTS types

3.2 Applications

Material selection and HTS design are fully dependent on the targeted application field. Here, critical requirements must be matched as e.g., power, currents, efficiency, operation temperature, cost and mechanical properties. Up to now, most of the superconductor applications are related to high-field magnets and/or low field measurements [42]. In general, superconducting materials are considered as an important enabling technology for various application as e.g. ([42]:

- Science: nuclear magnetic resonance (NMR), advanced high energy particle accelerators,
- Medical: Ultra-strong magnetic field generation for high-resolution magnetic resonance imaging (MRI) systems
- Transportation: high-speed maglev transportation,
- Industrial: Induction heaters, motors, generators
- Energy: Nuclear fusion reactors, high-capacity loss-less electric power transmission, superconducting energy storage (SMES), superconducting fault current limiters (SFCL)

The energy sector applications are of particular but not of exclusive interest in frame of the COST action [3]. The following sectors will be considered as frame for the mapping of activities carried out herein (based on the COST proposal):

- **Generation:** some power offshore HTS wind generators have been developed [43], e.g. in the EcoSwing Horizon 2020 project. Fault current limiters (FCL), deployed worldwide [44]–[47], allow integration of distributed generators, delaying/avoiding investments of upgrading protections or reinforcing the grid.

- **Transmission and distribution:** HTS power cables allow high current operation, sparing transformers in substations [48]. An MgB_2 high-current DC transmission line was also demonstrated at CERN. Compact HTS transformers [49] allow overload operation without lifetime degradation.

- **Energy storage:** flywheels with HTS contactless bearings store energy in a spinning mass, which can be delivered to the grid e.g. in uninterruptible power supply applications [50]. Superconducting Magnetic Energy Storage (SMES) systems store energy in superconducting coils, delivering high powers (kW-MW) in short times (ms-s) [51]. However, SMES do not play any role in energy storage today. Because of their high power density at very low energy density, SMES can be described rather than energy storage devices because of their high energy storage. SMES have the advantage of direct energy storage. There are no rotating parts, and chemical processes for energy conversion are not required. On the other hand, they have very high costs and large thermal losses.

- **Energy use:** Synchronous motors for ship propulsion in the range of 5 to 36.5 MW [52]. Industrial induction heating systems use HTS magnets to generate high DC magnetic fields, allowing to improve the efficiency of industrial aluminium heaters from around 50% (with conventional AC copper coils) to more than 80% (with HTS DC coils) [53], [54].

The participants of the survey were asked to indicate for which defined application they consider their HTS (Figure 8)-. It can be seen, that in particular SFCL, Motors Generator as well as cables are the most targeted applications. Only Aviation was named, as a non-energy area-based application. SMES, Nuclear fusion and aviation play only a minor role in this state-of-the-art snippet.

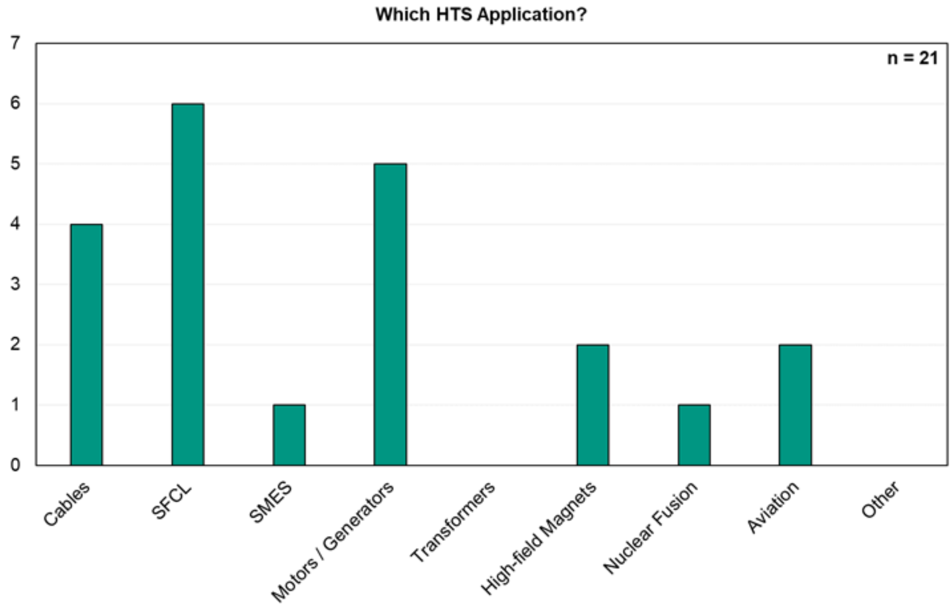

Figure 8: Overview of targeted application fields

The result s for future importance of different HTS application is indicated in Figure 9. Perceptions about the relevance of named application field are very different to the current research foci are indicated in the fig XX. Nuclear fusion, cables and aviation are seen as the most important application fields. It is, however, hardly distinguishable which application is more important to another one as the number of participants is rather low. This is in line with the screened literature related to LCA and techno-economics, where mostly cables where in the focus of the assessments.

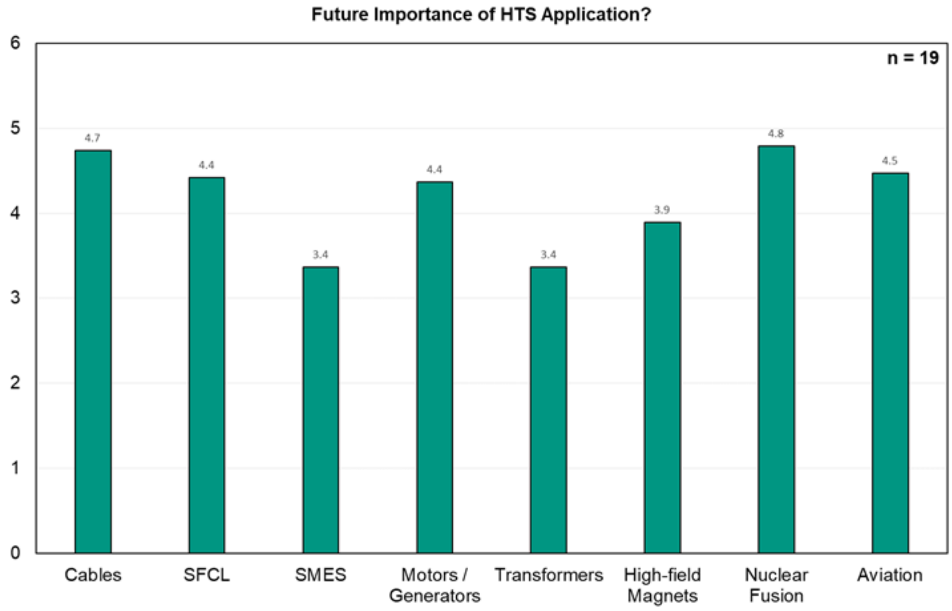

Figure 9: Overview of the perceived relevance of considered applications fields for HTS

3.3 Life cycle assessment studies for HTS

As stated before, results for LCA are very dependent on the selected application field which determines the design of a HTS. However, a goal of the survey is also to capture the expectations regarding environmental impacts. Participants were thus asked to indicate the most environmentally impactful life cycle phase out of their perspective as indicated in Figure 10.

Here most participants expect raw materials extraction, use and maintenance and the end of life phase as equally important. Only minor relevant is attributed to design and production and packaging and distribution. It should be noted that most participants are not experienced in the field of LCA and environmental impacts assessment.

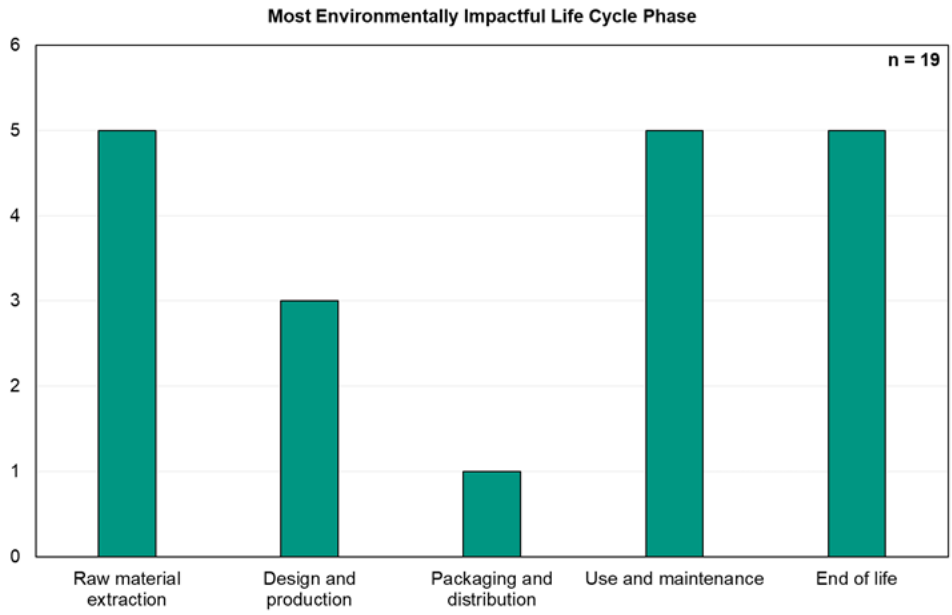

Figure 10: Overview of most expected environmental impact divided into different life phases for HTS

These expectations stand in sharp contrast to current LCA literature. Here a short summary of available LCA literature is provided. All reports are structured alongside their application and are finally compared in Table 1and Table 2. Special attention is given to the type of material analysed, its application, the considered components required for HTS operation and the final results. Additionally, comments are given for each study. This allows to identify if there are significant gaps in LCA regarding the considered literature, which allows to give some recommendations for future research in the field.

3.3.1 Power transmission and conversion devices

The authors of Hirose et al. [55], which is a rather old study published in 2006, conducted a LCA for a 66-kV, 3-kA (350-MVA) AC HTS cable ($Bi_2Sr_2Ca_2Cu_3O$ (BSCCO)). A comparative assessment of three conventional 275-kV 1x1,000 mm2 OF cables (duct installed) having the same capacity as that of the HTS cable was realized. Results indicate, that compared to CO_2 emissions during manufacturing, both types of cables emit significantly large amounts of CO_2 during their operation. A major challenge named is that a more accurate and updated LCA regarding the raw materials used is required.

The authors of Buchholz et al. [56] compared the environmental impacts of a high-temperature superconducting 10 kV cable system (ReBCO), to a conventional 10 kV cable system and a conventional 110 kV cable system. A cradle-to-grave approach (from raw material extraction up to the end-of-life) was used to do so. The functional unit refers to the annual transmitted electricity of cables with a nominal power $S_n \leq 40$ MVA assuming a lifetime of components of 40 years. Used LCA methods greenhouse gas emissions and cumulative energy demand. Results indicate, that environmental impacts are mostly caused by grid losses and liquid nitrogen consumption during the use phase. The Material and production phase do not affect the environmental performance. which is in line with Hirose et al. [55]. In general, Superconducting 10 kV cables can be used as an environmentally friendly alternative to conventional 10 kV cables. However, they cannot compete with conventional 110 kV cables without adjusting the transformer configuration.

The authors alongside Berti et al. [57] aim to compare the environmental performances of three 25 MVA transformers: i) BSCCO tape windings; ii) YBCO coated conductors windings; iii) and finally a paper-oil insulated transformer with copper windings. The used cooling system for both HTS is LN2 with varying dimensions. The conventional transformer uses a typical Oil Air Natural ONAN cooling system. The functional unit here was the transformation of 150 kV AC voltage to 20 kV supplying a maximum power of 25 MVA over a life time of 30 years. It is a cradle to grave approach wherein recycling of the transformers has been considered. Again, results indicate that use phase is the main cause of the life-cycle environmental burden (here up to 99% of the assessed impact categories as e.g.. total primary energy consumption, Human toxicity and Greenhouse effect over 20 years). In contrary, environmental impacts of transportation and installation phases account less than 1%of the HTS transformer. Production has contributed with about 2% to overall impacts. It is also worth mentioning that authors found out that a compensation greater than 80% of the raw material acquisition impacts and Greenhouse gas emissions effect is achievable using closed-loop metal recycling The YBCO based transformer is the most environmental-friendly due to reduces energy losses and used raw materials for production.

In frame of the project BEST PATHS ("BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal HVDC Systems"), Marian et al. [58] analysed a monopole cable system based on MgB2 wires and operating in helium gas at 10 kA and 320 kV. As in most other LCA studies, the highest impact can be allocated to the cooling of the system (here an outer cryogenic envelope with He and the inner one with N2). The only exceptions depending on the impact category are abiotic depletion, photochemical oxidation, acidification and eutrophication where the MgB2 wires dominate impacts due to the use of raw materials. Based on these results a major recommendation is to focus research effort on bringing the thermal losses of superconducting cables to an acceptable level when compared to the Joule losses of resistive cables [58].

3.3.2 Energy storage

The authors of this rather old work of Hartikainen et al. [59] aimed to analyse the environmental impacts of superconducting machinery compared to suitable devices used in decentralized electricity generation networks (DGs). In particular SMES, flywheels (45 units of 10 kWh Boeing flywheels with superconducting YBCO bearings) and batteries are compared. An LTS based SMES (NbTi-based system with liquid-helium cooling and an in-situ liquefier) is analysed and marked as non-competitive system to the other named options. The SMES units offers only a better performance to the other storage devices if HTS are incorporated. Also, significant potential of HTS based cables is stated for DGs [59], [60] .

3.3.3 Motors / Generators

Lloberas-Valls et al compared a 15 MW 2G HTS superconducting direct-drive synchronous generator for wind energy applications to a permanent-magnet direct-drive synchronous generator. As a functional unit, they chose the generation of 15 MW using a direct-drive generator for wind energy applications with a low shaft speed of 7 r/min and a minimum efficiency of 95%. However, they only considered the production phase of both generators and thus applied the cradle-to-gate approach. For the superconducting generator, they identified the steel for stators and rotors as the main contributor to six out of eight considered impact categories. The superconducting YBCO tape is the major contributor in the eutrophication potential category. In direct comparison, the production phase of the permanent-magnet direct-drive generator has higher impacts than the superconducting generator in most categories. However, while the components of the cooling unit are included in their study, the actual cooling during the use phase is not.

Table 1: Summary of reviewed LCA studies related to HTS

Source	**Year**	**Goal**	**Material**	**Application**	**Considered components**	**Results**	**Comment**
				Power transmission and conversion devices			
Hirose et al. [55]	2006	superconducting cable systems (A 66-kV, 3-kA (350-MVA) AC HTS)	Bi2Sr2Ca2Cu3	Power transmission, duration 30 years, load factor 1	N/A	Competitive to conventional alternatives	Only very limited information is provided about the used LCI, the assessment method or used software
Buchholz et al. [56]	2021	10 kV cable system (ReBCO) vs. Two conventional systems 10 kV and 110 kV	ReBCO	Power transmission	Cooling and wires	Use phase dominates due to heat losses and corresponding cooling efforts	transformer configuration has to be adjusted to make wires competitive
Marian et al. [58]	2017	HVDC Superconducting Cable	MgB2	Power Transmission	Cooling and wires	Use phase dominates due to heat losses and corresponding cooling efforts	State that minimizing heat losses should make HTS wires competitive
Berti et al [57]	2009	2 HTS based vs. conventional 25 MVA transformers	BSCCO, YBCO, conventional transformer	Power transformation	Cooling wires, and recycling	Use phase dominates due to heat losses	
				Energy storage			
Hartikainen et al. [59]	2007	SMES using LTS and Flywheels using HTS	YBCO	SMES LTS and explorative with HTS, Flywheel with HTS bearings	Not clear	LTS not competitive, HTS based SMES could be competitive in environmental regard.	YBCO LCI are not available
				Motors and generators			

Lloberas-Valls et al	2015	LCA comparison between 15-MW 2G HTS and permanent-magnet direct-drive synchronous generators for offshore wind energy applications	YBCO	Generators for wind turbines	HTS tapes, cooling system materials	Abiotic resource depletion, eutrophication, acidification are higher in HTS due to Hastelloy	Use phase not included

3.4 Techno-economic assessment for HTS

Thus, a similar question as in the case of LCA was carried out for the greatest economic challenge of HTS in frame of the survey. The leading question was “How do you rate the economic challenges for the future?”. In total 19 participants responded fully to the survey as depicted in Figure 11. It can be seen that most participants consider the cooling unit / cryocooler as the biggest economic challenge, followed by the used HTS material and cryostat. The other categories are considered to have less impact in this regard.

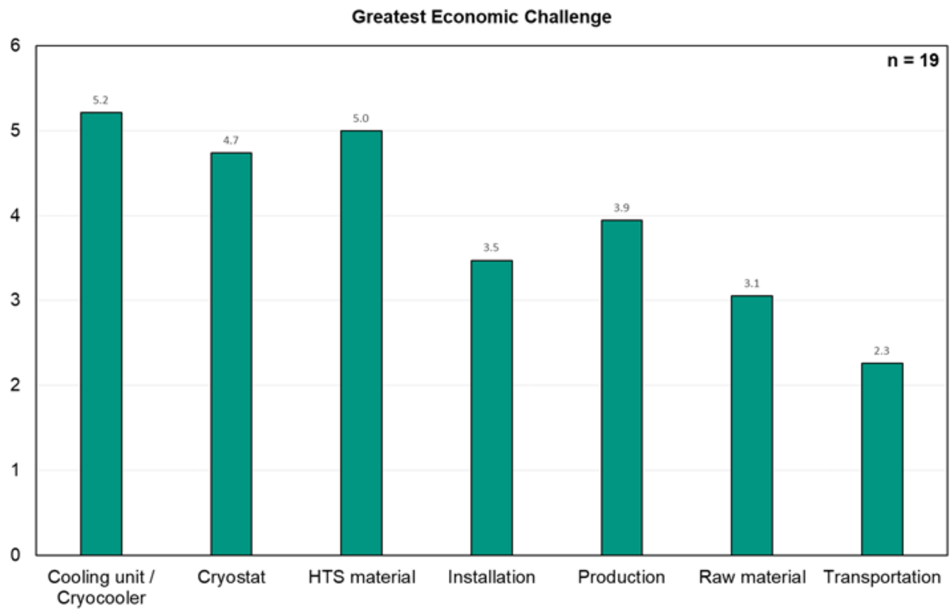

Figure 11: Overview of expected greatest economic challenges for HTS

In the following some studies focussing on techno-economics have been reviewed as in the case of LCA. Again, studies are characterized by their application field. Where possible and considered useful, detailed findings are summarized.

3.4.1 Energy transmission and conversion

Within this study, which was already presented in the section about LCA Hirose et al. [55] authors analysed the economic performance of a Bi2Sr2Ca2Cu3O (BSCCO) high-temperature superconducting (HTS) wire. In more detail, cable reliability from the perspectives of lifespan and failure, economic efficiency from transmission loss reduction and energy saving performance, and environmental performance was analysed. Taking 1,500 MVA power transmission route as an example, authors concluded that HTS cables have reached the stage of actual utilization comparison between the existing AC cables, HTS AC cables, and HTS DC cables regarding factors as loss, energy-saving and economic efficiency.

In this work of Nasser et al., [61] authors analyse the integration of High Temperature Superconducting (HTS) cables into distribution networks and the related techno-economic performance. Authors provide a good overview of most recent projects integrating of HTS cables into the supply networks. Here they state that HTS are beneficial especially in case of dramatically increase of load demand with the right-of-Way (ROW) restrictions. The grid is operated at 20 KV using two high voltage power stations with two transformers of 110/20 kV and each of 33.5 MVA. Conventional HV cables, HV overhead lines, and MV conventional cables are compared with the MV-HTS cables regarding technical and economic issues. In total, 5 scenarios were analysed considering different time horizons have been considered today, 2030, and 2050. Authors conclude that using HTS is highly cost competitive in the future of this scenario. However, they also state that more analyses are needed, considering e.g., N − 1 contingency analysis and short circuit analysis as well as analysis with the existence of load and generation profiles.

Noe et al. [62] focus on the ow the consequence of a large-scale integration of superconducting power equipment in distribution level urban power systems. In total three scenarios were developed and compared to a conventional present structure of an urban area electrical power grid. The HTS scenarios start from the replacement of an existing distribution level sub-grid up to a full superconducting urban area distribution level power system. The techno-economic evaluation includes costs for investment, operation and losses, but does not take into account CO2 emission or additional costs for CO2. Including the latter would potentials have led to better results for HTS. Results for all scenarios indicate where annual costs are comparable with the conventional grid case. The sensitivities carried out show, that he higher the load density, the more favourable are the HTS scenarios, due to increased savings in losses.

3.4.2 Energy storage

Colmenar Santos *et al.* [63] analysed a SMES application to the case of the Spanish electrical system. Results indicate that there is a lack of legislative and economic aspects for the inclusion of energy reserve by a superconducting magnetic energy storage. Unfavourable commercial position compared to other storage systems due to comparable high costs of manufacturing and operation.

Zhu *et al.* [64] focused on the application of a 5 MJ SMES in a practical renewable power system in China and performed an economic analysis. The economic feasibility is analyzed by comparing the cost and the savings from wind power curtailment of deploying SMES and battery. In particular the SMES operation is evaluated considering the wind turbine failure and the SMES location in Zhangbei wind farm power grid. Economic feasibility assessment is based on the investment deferral (delaying investments in electrical grid) and the payback period of the SMES. The latter indicates when the investment becomes profitable in terms of years. Three scenarios are calculated to do so I) wind curtailment, ii) network investment and iii) SMES and battery investment. Results show that in general SMES can be considered a promising measure to stabilize wind energy fluctuations. In economic terms, SMES is currently not competitive to conventional network reinforcement. However, declining cost and increasing performance of HTS could lead to an improvement in these regards.

Soman *et al.* [65] analysed in detail the economic aspects of using superconducting magnetic energy storage (SMES) systems and high-temperature superconducting (HTS) transformers. A corresponding review of reports published by utilities and other projects was realized to do so. It is concluded that HTS transformers are only an option in applications with weight and transport restrictions (in highly populated areas, ships etc.). In any case conclude that a detailed cost breakdown model is required for an actual

SMES device to better estimate investment costs, which seems to be a major gap in research at this stage as cost ranges differ significantly across various works studied.

3.4.3 Motors and generators

As part of the EolSupra20 project, Hoang et al. [66] carried out a LCOE analysis for a 20 MW fully superconducting wind turbine generator. The machine uses magnesium diboride (MgB2) superconductors for both the rotor and stator windings. The analysis included the magnetic and thermal design with special attention devoted to the cryogenic system. The LCOE was compared to the one of a conventional 20 MW permanent magnet synchronous generator (PMSG). To make a fair comparison, both machines where optimized using a 2-D finite element method-based optimization to minimize the levelized cost of energy. The results indicate that the LCOE can be reduced by 8.5%. This is the consequence of a lighter generator (2.5 times lighter than the PMSG) that allows to reduce the investment cost for the tower and floating foundation.

Table 2: Overview of techno-economic assessments related to HTS within different applications

Source	Year	Goal	Material	Application	Considered cost	Results	Comment
Power transmission and conversion devices (transformers)							
Hirose et al. [55]	2006	superconducting cable systems	Bi2Sr2Ca2Cu3	Power transmission	N/A	Competitive to conventional alternatives	
Soman et al. [65]	2008	economic aspects HTS based SMES systems and transformers	No information about considered HTS materials	SMES and transformer (e.g. 18MVA HTS vs. 24 MVA conventional	See publication	similarly rated conventional unit	more utility scale studies need
Noe et al.	2010	large-scale integration of superconducting power equipment in distribution level urban power systems	No information about considered HTS material	Electricity distribution in distribution level urban power systems	investment, operation and losses	costs are comparable with the conventional grid case	Considering CO2 cost could lead to better results for HTS.
Energy storage (SMES) and hybrid energy storage X+ SMES							
Colemar et al [63]	2018	regulatory framework and the economic aspects	General overview regulatory framework and the economic aspects	Energy Storage	costs of manufacturing and maintenance	High costs of manufacturing and operation	State that there is a general ack of institutional support energy storage
Soman et al. [65]	2008	SMES	Not specified	SMES for wind turbines, DC interconnected systems and FACTs	Provide rough cost bread down of main components	State that more utility scale studies are required to evaluate economic benefits	Provide a good overview

Zhu et al. [64]	2018	SMES	Not specified	cost and the savings from wind power curtailment of deploying SMES and battery	Investment and operation	promising measure to stabilize wind outputs but not competitive to conventional network reinforcement	declining cost could lead to better performance
Motors and generators							
Hoang et al. [66]	2018	Wind turbine generator	MgB2	Electricity generation	capital and operational expenditures, as well as the decommissioning cost	The LCOE of a 20 MW superconducting wind turbine generator might be lower than the one of a conventional 20 MW generator	LCOE comparison

4 Multidimensional and other Assessments as material criticality

There are further methods for the sustainability or techno-economic assessment available to analyse HTS. Some of these are e.g., optimization models with either mono objective goals or as in the case of sustainability with multi-objective problems.

Optimization is always an efficient and effective way to reduce the cost for a HTS system. In the cost optimization, the performance of the HTS system, such as the magnet generated, is usually a key requirement. Thus, more accurate simulation tools, such as Finite Element Analysis (FEA), are desired to obtain better performance. However, those numerical simulation tools are always time-consuming. For example, one FEA simulation for a solenoid magnet using HTS tape may spend half to one hour for one single run. Considering the optimization requiring large amounts of simulations, it is challenging to perform simulation-based optimization by using traditional optimization algorithms (e.g., Genetic Algorithm). As a result, new optimization algorithms, involving surrogate modelling and other machine learning methods are developed to deal with the high computational cost simulation-based optimization problems. However, the surrogated model-based optimization algorithms are hardly used in the HTS system design area. To obtain better performance with lower cost, the high efficient optimization algorithms should be developed for the HTS system.

Together with the energy transition, concerns have been raised about the supply of raw materials and minerals. Generally, clean technologies require more minerals to build than their fossil fuel-based counterparts. An electric car for example generally requires six times the mineral inputs of a conventional one [67]. Securing reliable, sustainable and undistorted access to certain raw materials and minerals is thus crucial for the EU and across the globe.

To address this concern, the European Commission has created a list of critical raw materials (CRMs) for the EU, which combine raw materials and minerals of high importance to the European economy and whose supply is associated with high risk. This list is revised every three years and it contains, as of 2020, 30 materials) as compared to 14 materials in 2011.

The competitiveness of HTS and its role in a climate-neutral energy system depends on the availability, affordability and responsibly sourced raw materials used. Besides a standard LCA of HTS applications, a deeper analysis of the materials used is thus crucial to understand the vulnerabilities along the supply chain and enhance its development. A corresponding assessment should be carried out considering typical raw materials used in HTS as e.g. MgB_2 or $Bi_2Sr_2Ca_2Cu_3$, to name some examples.

Table 3 : 2020 critical raw materials [68]

Antimony	Hafnium	Phosphorus
Baryte	Heavy Rare Earth Elements	Scandium
Beryllium	Light Rare Earth Elements	Silicon metal
Bismuth	Indium	Tantalum

Borate	Magnesium	Tungsten
Cobalt	Natural graphite	Vanadium
Coking coal	Natural rubber	Bauxite
Fluorspar	Niobium	Lithium
Gallium	Platinum Group Metals	Titanium
Germanium	Phosphate rock	Strontium

5 Identification of Gaps for HTS and recommendations for future activities

The literature review showed that there is already some literature available about LCA and techno-economic assessments. However, several studies date back over 10 years and most of them do not provide in depth information about the modelling. This is the case for most of the LCA studies analysed. Reviewed studies on do not always follow the standard 4 steps of LCA and do not provide in-depth data related to their LCI. In general, there is a lack of up-to-date data for all reviewed fields (Motors and Generators, energy storage and transmission). Furthermore, most of the LCA literature does not cover the entire product life cycle of an HTS tape and often only focuses on the used materials without including the use phase and in particular end of life (only one study did this in a tentative way). In other cases, the focus is on only one or only a few environmental impact categories (mostly CO_2). While this allows a first assessment, focusing only on one impact category can lead to a neglection of disadvantages in other categories.

In the following some recommendations regarding future activities will be provided. These activities will not necessarily be all covered in frame of the Cost action, but we hope that the discussion will serve as a starting point for future assessments. Naturally, some of the given recommendations for LCA are overlapping with the ones for techno-economics.

Life Cycle Assessment

- Best practice recommendations for LCA dealing with HTS technologies should be prepared, in order to allow comparison between two studies.
- Database for LCIs for different HTS could be shared

Techno-economic Assessments

- A collaborative cost database for wire, tapes and bulks could be set up
- Similarly, to LCA, best practice recommendations for techno-economics dealing with HTS technologies should be prepared, in order to allow comparison between two studies.

System Perspective (LCA and techno-economics)

- In general, HTS systems, no matter for which application, require a cooling system comprised of pumps and a cryocooler. Consequently, maintenance technologies for these equipment's must be established and verified when carrying out a LCC or LCA for an entire HTS System as in case of [55]. The named component as well as use phase is of major interest and considered in the survey as well as literature review.
- Entire System perspective wherein scenarios are developed where HTS is used on a wide systemic scale. This can help to understand how this could change the system in face of massive electrification until 2050. One example could be e.g. Wind turbines in Europe and to compare conventional vs. new design HTS based ones.

6 Conclusion

The overall task of the deliverable is to provide a mapping report of the field within the cost action. In line with this data gaps, main applications and main materials (related to techno-economics and environmental aspects) are identified via an online survey. This assessment is flanked by a comprehensive literature review on the environmental and techno-economic assessment of HTS. Additionally, it provides basic knowledge on the named methods for non-LCA or techno-economic assessment experts to broaden their perspective in frame of HTS technology development. The given recommendations can be seen as a starting point for further activities related to the assessment of HTS. In any case, there is a big lack of transparent, in-depth studies that allow it to reconstruct named assessments. Also, there is almost no public primary data available to carry out comparison among different systems within different applications. Last but not least, more up-to date assessments on HTS are required.

Bibliography

[1] M. Tomita and M. Murakami, “High-temperature superconductor bulk magnets that can trap magnetic fields of over 17 tesla at 29 K,” *Nature*, vol. 421, no. 6922, pp. 517–520, Jan. 2003, doi: 10.1038/nature01350.

[2] D. Uglietti, “A review of commercial high temperature superconducting materials for large magnets: from wires and tapes to cables and conductors,” *Supercond. Sci. Technol.*, vol. 32, no. 5, p. 053001, May 2019, doi: 10.1088/1361-6668/ab06a2.

[3] COST, “Hi-Scale Technical Annex,” Proposal, 2020.

[4] J. K. Musango and A. C. Brent, “A conceptual framework for energy technology sustainability assessment,” *Energy Sustain. Dev.*, vol. 15, no. 1, pp. 84–91, Mar. 2011, doi: 10.1016/j.esd.2010.10.005.

[5] A. Grunwald, “Sustainability Assessment of Technologies - An Integrative Approach,” in *Sustainable Development - Energy, Engineering and Technologies - Manufacturing and Environment*, 2012, pp. 35–62.

[6] J. Goldemberg and World Resources Institute, Eds., *Energy for a sustainable world*. Washington, DC, USA: World Resources Institute, 1987.

[7] S. Bell, *Engineers, society, and sustainability*. San Rafael, Calif.: Morgan & Claypool, 2011. Accessed: Feb. 03, 2014. [Online]. Available: http://dx.doi.org/10.2200/S00378ED1V01Y201108ETS017

[8] J. Robinson, “Squaring the circle? Some thoughts on the idea of sustainable development,” *Ecol. Econ.*, vol. 48, no. 4, pp. 369–384, Apr. 2004, doi: 10.1016/j.ecolecon.2003.10.017.

[9] G. Brundtland, “Report of the World Commission on Environment and Development: Our Common Future,” United Nations World Commission on Environment and Development (WCED), Oslo, Mar. 1987.

[10] T. Kuhlman and J. Farrington, “What is Sustainability?,” *Sustainability*, vol. 2, no. 11, pp. 3436–3448, Nov. 2010, doi: 10.3390/su2113436.

[11] United Nations, “Transforming our world: the 2030 Agenda for Sustainable Development,” New York, Resolution adopted by the General Assembly on 25 Se ptember 2015, Oct. 2015. [Online]. Available: http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E

[12] United Nations, “The Sustainable Development Goals Report 2020,” United Nations, 2020. Accessed: Oct. 25, 2021. [Online]. Available: https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf

[13] Federal Ministry for Economic Affairs and Energy, “Our energy transition for an energy supply that is secure, clean, and affordable,” Jun. 2019. https://www.bmwi.de/Redaktion/EN/Dossier/energy-transition.html

[14] UNEP, “Life Cycle Initiative - What is Life Cycle Thinking,” *What is Life Cycle Thinking?*, 2021. https://www.lifecycleinitiative.org/starting-life-cycle-thinking/what-is-life-cycle-thinking/

[15] A. Grunwald, *Technikfolgenabschätzung- eine Einführung*, vol. 1. Berlin: Edition Sigma, 2002.

[16] A. Grunwald, *Rationale Technikfolgenbeurteilung: Konzepte und methodische Grundlagen*, vol. 1. Berlin-Heidelberg: Springer, 1999.

[17] ISO, “ISO 14040 – Environmental management – Life Cycle Assessment – Principles and framework,” International Organization for Standardization, Geneva, Switzerland, 2006.

[18] ISO, “ISO 14044 – Environmental management – Life Cycle Assessment – Requirements and guidelines,” International Organization for Standardization, Geneva, Switzerland, 2006.

[19] European Commission, “Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment,” Joint Research Center & Institute for Environment and Sustainability, Ispra, 2010.

[20] H. Hottenroth, J. Peters, M. Baumann, T. Viere, and I. Tietze, “Life-cycle Analysis for Assessing Environmental Impact,” in *Issues in Environmental Science and Technology*, R. E. Hester and R. M. Harrison, Eds. Cambridge: Royal Society of Chemistry, 2018, pp. 261–295. doi: 10.1039/9781788015530-00261.

[21] European Commission, Joint Research Centre, and Institute for Environment and Sustainability, *International Reference Life Cycle Data System (ILCD) handbook framework and requirements for life cycle impact assessment models and indicators.* Luxembourg: Publications Office, 2011.

[22] M. J. Baumann, J. F. Peters, M. Weil, and A. Grunwald, “CO2 footprint and life cycle costs of electrochemical energy storage for stationary grid applications,” *Energy Technol.*, Dec. 2016, doi: 10.1002/ente.201600622.

[23] B. S. Dhillon, *Life cycle costing for engineers*. Boca Raton, FL: Taylor & Francis, 2010.

[24] Davis Langdon Management Consulting, “Literature review of life cycle costing (LCC) and life cycle assessment (LCA),” Davis Langdon Management Consulting, Working Paper, Jul. 2005.

[25] Christoph Kost, J. Mayer, and J. Thomsen, “Levelized Cost of Electricity Renewable Energy Technologies,” Fraunhofer Institut for Solar Energy Systems (ISE), Nov. 2013. [Online]. Available: http://www.ise.fraunhofer.de/en/publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/study-levelized-cost-of-electricity-renewable-energies.pdf
[26] O. Schmidt, S. Melchior, A. Hawkes, and I. Staffell, “Projecting the Future Levelized Cost of Electricity Storage Technologies,” *Joule*, vol. 3, no. 1, pp. 81–100, Jan. 2019, doi: 10.1016/j.joule.2018.12.008.
[27] IEC, “IEC 60300-3-3, Part 3-3: Application guide – Life cycle costing,” International Electrotechnical Commission, Geneva, Switzerland, 2004.
[28] VDI, “VDI 2884: Beschaffung, Betrieb und Instandhaltung von Produktionsmitteln unter Anwendung von Life Cycle Costing (LCC) Purchase, operating and maintenance of production equipment using Life Cycle Costing (LCC),” VEREIN DEUTSCHER INGENIEURE, Berlin, 2006.
[29] G. Wöhe Döring, Ulrich, *Einführung in die allgemeine Betriebswirtschaftslehre*. München: Vahlen, 2013.
[30] R. Brugger, *Der IT Business Case Kosten erfassen und analysieren, Nutzen erkennen und quantifizieren, Wirtschaftlichkeit nachweisen und realisieren*. Berlin: Springer, 2005. Accessed: Mar. 25, 2014. [Online]. Available: http://public.eblib.com/EBLPublic/PublicView.do?ptiID=417688
[31] S. Fuller and A. Boyles, “LIFE-CYCLE COSTING WORKSHOP FOR ENERGY CONSERVATION IN BUILDINGS: STUDENT MANUAL,” U.S. DEPARTMENT OF COMMERCE, Gaithersburg, Apr. 2000.
[32] Y. Krozer, “Life cycle costing for innovations in product chains,” *J. Clean. Prod.*, vol. 16, no. 3, pp. 310–321, Feb. 2008, doi: 10.1016/j.jclepro.2006.07.040.
[33] S. Raikar and S. Adamson, “Renewable energy finance in the international context,” in *Renewable Energy Finance*, Elsevier, 2020, pp. 185–220. doi: 10.1016/B978-0-12-816441-9.00013-1.
[34] S. Comello and S. Reichelstein, “The emergence of cost effective battery storage,” *Nat. Commun.*, vol. 10, no. 1, p. 2038, Dec. 2019, doi: 10.1038/s41467-019-09988-z.
[35] P. Paganis, M. Pica, and et. al, “Code of Practice for Life Cycle Costing (Code de bonne conduite pour une évaluation du coût global de possession),” NATO Research Technology Organisation, 2009.
[36] VDI, “VDI 2885: Standardized data for maintenance planning and determination of maintenance costs - Data and data determination,” Verein Deutscher Ingenieure, Berlin, 2003.
[37] Z. Melhem, Ed., *High temperature superconductors (HTS) for energy applications*. Oxford ; Philadelphia, PA: Woodhead Pub, 2012.
[38] A. Bussmann-Holder and H. Keller, “High-temperature superconductors: underlying physics and applications,” *Z. Für Naturforschung B*, vol. 75, no. 1–2, pp. 3–14, Feb. 2020, doi: 10.1515/znb-2019-0103.
[39] A. Ballarino and R. Flükiger, “Status of MgB_2 wire and cable applications in Europe,” *J. Phys. Conf. Ser.*, vol. 871, p. 012098, Jul. 2017, doi: 10.1088/1742-6596/871/1/012098.
[40] Y. Kamihara, T. Watanabe, M. Hirano, and H. Hosono, “Iron-Based Layered Superconductor $La[O_{1-x}F_x]FeAs$ (x = 0.05−0.12) with T_c = 26 K,” *J. Am. Chem. Soc.*, vol. 130, no. 11, pp. 3296–3297, Mar. 2008, doi: 10.1021/ja800073m.
[41] H. Hosono *et al.*, “Exploration of new superconductors and functional materials, and fabrication of superconducting tapes and wires of iron pnictides,” *Sci. Technol. Adv. Mater.*, vol. 16, no. 3, p. 033503, Jun. 2015, doi: 10.1088/1468-6996/16/3/033503.
[42] C. Yao and Y. Ma, “Superconducting materials: Challenges and opportunities for large-scale applications,” *iScience*, vol. 24, no. 6, p. 102541, Jun. 2021, doi: 10.1016/j.isci.2021.102541.
[43] A. B. Abrahamsen *et al.*, “Superconducting wind turbine generators,” *Supercond. Sci. Technol.*, vol. 23, no. 3, p. 034019, Mar. 2010, doi: 10.1088/0953-2048/23/3/034019.
[44] A. Hobl, W. Goldacker, B. Dutoit, L. Martini, A. Petermann, and P. Tixador, “Design and Production of the ECCOFLOW Resistive Fault Current Limiter,” *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, pp. 5601804–5601804, Jun. 2013, doi: 10.1109/TASC.2013.2238288.
[45] F. Moriconi, F. De La Rosa, F. Darmann, A. Nelson, and L. Masur, “Development and Deployment of Saturated-Core Fault Current Limiters in Distribution and Transmission Substations,” *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 1288–1293, Jun. 2011, doi: 10.1109/TASC.2011.2104932.
[46] Yin Xin *et al.*, “Manufacturing and Test of a 35 kV/90 MVA Saturated Iron-Core Type Superconductive Fault Current Limiter for Live-Grid Operation,” *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 1934–1937, Jun. 2009, doi: 10.1109/TASC.2009.2018510.
[47] R. Kreutz *et al.*, “System Technology and Test of CURL 10, a 10 kV, 10 MVA Resistive High-Tc Superconducting Fault Current Limiter,” *IEEE Trans. Appiled Supercond.*, vol. 15, no. 2, pp. 1961–1964, Jun. 2005, doi: 10.1109/TASC.2005.849345.

[48] J. F. Maguire, F. Schmidt, S. Bratt, T. E. Welsh, and Jie Yuan, "Installation and Testing Results of Long Island Transmission Level HTS Cable," *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 1692–1697, Jun. 2009, doi: 10.1109/TASC.2009.2018221.

[49] T. Bohno *et al.*, "Development of 66kV/6.9kV 2MVA prototype HTS power transformer," *Phys. C Supercond. Its Appl.*, vol. 426–431, pp. 1402–1407, Oct. 2005, doi: 10.1016/j.physc.2005.03.080.

[50] M. Strasik *et al.*, "Design, Fabrication, and Test of a 5-kWh/100-kW Flywheel Energy Storage Utilizing a High-Temperature Superconducting Bearing," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 2133–2137, Jun. 2007, doi: 10.1109/TASC.2007.898065.

[51] G. Zhang *et al.*, "The Construction Progress of a High-Tc Superconducting Power Substation in China," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 2824–2827, Jun. 2011, doi: 10.1109/TASC.2010.2098471.

[52] S. S. Kalsi, B. B. Gamble, G. Snitchler, and S. O. Ige, "The status of HTS ship propulsion motor developments," in *2006 IEEE Power Engineering Society General Meeting*, Montreal, Que., Canada, 2006, p. 5 pp. doi: 10.1109/PES.2006.1709643.

[53] A. B. Abrahamsen, N. Magnusson, B. B. Jensen, and M. Runde, "Large Superconducting Wind Turbine Generators," *Energy Procedia*, vol. 24, pp. 60–67, 2012, doi: 10.1016/j.egypro.2012.06.087.

[54] Y. H. Choi *et al.*, "A Tabletop Persistent-Mode, Liquid Helium-Free 1.5-T MgB_2 'Finger' MRI Magnet: Construction and Operation of a Prototype Magnet," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–5, Aug. 2019, doi: 10.1109/TASC.2019.2900057.

[55] M. Hirose, Y. Yamada, T. Masuda, K.-I. Sato, and H. Ryosuke, "Study on Commercialization of High-TemperatureSuperconductor," *SEI Tech. Rev.*, vol. 62, pp. 1–23, Jue 2006.

[56] A. Buchholz, M. Noe, D. Kottonau, E. Shabagin, and M. Weil, "Environmental Life-Cycle Assessment of a 10 Kv High-Temperature Superconducting Cable System for Energy Distribution," *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, pp. 1–5, Aug. 2021, doi: 10.1109/TASC.2021.3070703.

[57] R. Berti, F. Barberis, V. Rossi, and L. Martini, "Compararison of the ecoprofiles of superconducting and conventional 25 MVA transformers using the life cycle assessment methodology," in *IET Conference Publications*, Prague, Czech Republic, 2009, pp. 773–773. doi: 10.1049/cp.2009.0974.

[58] A. Marian *et al.*, "An MgB2 HVDC Superconducting Cable for Power Transmission with a Reduced Carbon Footprint," in *Eco-design in Electrical Engineering*, vol. 440, J.-L. Bessède, Ed. Cham: Springer International Publishing, 2018, pp. 129–135. doi: 10.1007/978-3-319-58172-9_14.

[59] T. Hartikainen, R. Mikkonen, and J. Lehtonen, "Environmental advantages of superconducting devices in distributed electricity-generation," *Appl. Energy*, vol. 84, no. 1, pp. 29–38, Jan. 2007, doi: 10.1016/j.apenergy.2006.04.011.

[60] T. Hartikainen, "The potential of the applications of superconductivity in greenhouse gas emission reduction," Tempere University of Technology, Tapereen, 2005. [Online]. Available: https://trepo.tuni.fi/bitstream/handle/10024/115190/hartikainen.pdf?sequence=1&isAllowed=y

[61] N. G. A. Hemdan, M. Kurrat, T. Schmedes, A. Voigt, and R. Busch, "Integration of superconducting cables in distribution networks with high penetration of renewable energy resources: Techno-economic analysis," *Int. J. Electr. Power Energy Syst.*, vol. 62, pp. 45–58, Nov. 2014, doi: 10.1016/j.ijepes.2014.04.021.

[62] M. Noe *et al.*, "Conceptual study of superconducting urban area power systems," *J. Phys. Conf. Ser.*, vol. 234, no. 3, p. 032041, Jun. 2010, doi: 10.1088/1742-6596/234/3/032041.

[63] A. Colmenar-Santos, E.-L. Molina-Ibáñez, E. Rosales-Asensio, and J.-J. Blanes-Peiró, "Legislative and economic aspects for the inclusion of energy reserve by a superconducting magnetic energy storage: Application to the case of the Spanish electrical system," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 2455–2470, Feb. 2018, doi: 10.1016/j.rser.2017.09.012.

[64] J. Zhu *et al.*, "Techno-economic analysis of MJ class high temperature Superconducting Magnetic Energy Storage (SMES) systems applied to renewable power grids," *Glob. Energy Interconnect.*, vol. Volume 1, no. Issue 2, pp. 172–178, Apr. 2018, doi: https://doi.org/10.14171/j.2096-5117.gei.2018.02.009.

[65] R. Soman *et al.*, "Preliminary Investigation on Economic Aspects of Superconducting Magnetic Energy Storage (SMES) Systems and High-Temperature Superconducting (HTS) Transformers," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 4, pp. 1–5, Jun. 2018, doi: 10.1109/TASC.2018.2817656.

[66] T.-K. Hoang, L. Quéval, C. Berriaud, and L. Vido, "Design of a 20-MW Fully Superconducting Wind Turbine Generator to Minimize the Levelized Cost of Energy," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 4, Jun. 2018, doi: IEEE Transactions on Applied Superconductivity.

[67] "The Role of Critical Minerals in Clean Energy Transitions," International Energy Agency, 2021. [Online]. Available: https://iea.blob.core.windows.net/assets/24d5dfbb-a77a-4647-abcc-667867207f74/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf

[68] EC, "Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability," European Commission, Brussels, Belgium: European Commission, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS COM(2020) 474 final, Sep. 2020.