IEA Technology Collaboration Programme on High-Temperature Superconductivity

2020 ANNUAL REPORT

Superconductivity
INTERNATIONAL ENERGY AGENCY

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Message from the Chair

Finally, hindsight is 2020. It was an inauspicious year that proved pivotal for our world. The seemingly endless pandemic challenged us to meet the moment, and in more ways than imagined, we did. A barrier for us emerged early in 2020 when the novel coronavirus broke out, just weeks before we were scheduled to host our TCP's spring meeting in Milan. Despite the pandemic, our TCP not only survived, but thrived in our new virtual setting. We rededicated our efforts by developing a new strategic workplan, embarked on the development of new technical and market-readiness roadmaps for HTS applications, and ended the year more engaged, productive, and connected than in the past.

While several utilities are selecting HTS applications like superconducting cables and fault current limiters, there is still work to do. As IEA has published, progress on energy efficiency is lagging worldwide, and 2020 tied two others years for the distinction of ***hottest year on record***.

To help address these issues, the High-Temperature Superconductivity TCP was extended for another five-year period. This agreement allows our nine-country-member program to continue its efforts to identify and evaluate the potential applications and benefits of superconductivity in the energy sector–and the barriers that stand in their way.

Opportunities to gather once again may reemerge in 2021 to renew our spirits and our capacity to recruit new countries, promote HTS at professional conferences, forge new partnerships, and work with one another to propel HTS toward a brighter future.

HTS TCP Executive Committee Chairman

Luciano Martini

Introduction to Applied Research

New demands are being placed on the electrical infrastructure to provide a more clean, digital and connected economy. High temperature superconductivity is one of the technologies that has the potential to provide a more reliable, flexible, resilient and secure transmission and distribution system.

Superconductivity is a phenomenon that causes certain materials, at low temperatures, to lose essentially all resistance to the flow of electricity. The lack of resistance enables a range of innovative technology applications. The temperature at which resistance ceases is referred to as the "transition temperature", or critical temperature (Tc). Tc is usually measured in kelvin (K)—0 K being absolute zero. HTS gets its name originally because it has a higher transition temperature (77 K, which can be achieved when using liquid nitrogen) than low temperature superconductivity (LTS) (around 4.2 K, which can be achieved using liquid helium).

End of termination of 80kV DC HTS Cable in Jeju Island, Korea.
Image Courtesy of KEPCO.

Several examples of well-recognized types of superconducting wire include:

- BSCCO, known as first generation (1G) HTS wire (Bismuth - Strontium - Calcium - Copper – Oxide)
- REBCO, known as second generation (2G) HTS wire (REBCO stands for "Rare earth - Barium - Copper Oxide" for the superconducting compound; REBCO is also referred to as YBCO since Yttrium (Y) is the element most often used in 2G wire)
- MgB_2 (Magnesium diboride)
- Nb_3Sn (Niobium-Tin) and Nb-Ti (Niobium-Titanium) alloys

A picture of Sieman's HTS-enabled Somatom X.cite CT scanner. *Image Courtesy of Siemens Healthineers.*

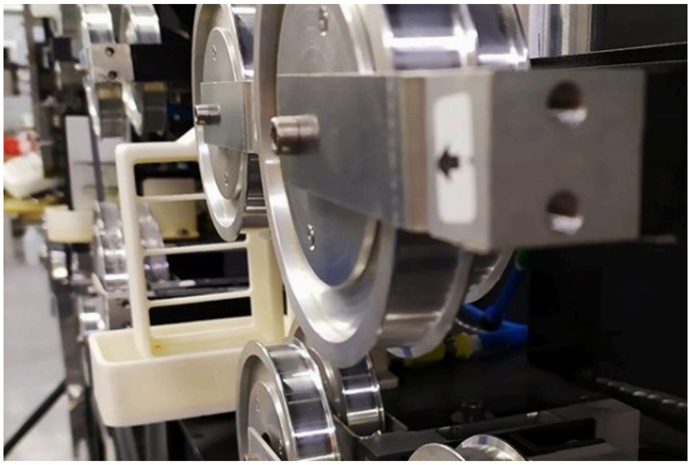
Another critical component of a superconductive device is the cryogenic (refrigeration) system for achieving operating temperatures. Low temperature superconductors operate at the "low" liquid helium temperature of (4 K or -296°C). High temperature superconducting (HTS) materials operate at the "high" temperature of liquid nitrogen (77 K or -196°C). Because liquid nitrogen (LN) is relatively ubiquitous and cheaper than liquid helium, HTS technologies offer greater potential to develop cost-effective solutions for the electric power sector

Since the discovery of HTS in 1986, research and development have brought new equipment enabled by high-temperature superconductivity to the threshold of electricity transmission and distribution applications. Superconductor-based devices provide improvements over conventional electric grid technologies, but they also offer unique alternatives to system challenges that cannot be addressed otherwise. Laboratory-scale tests have transitioned to large-scale HTS based projects that serve utility customers. HTS projects are now part of permanent infrastructure installations to solve real-world electric grid problems.

Applications of superconductivity have been available in certain niche markets for decades. Superconducting magnets, in particular, are well-established in many applications that require powerful electromagnets like high-energy-physics particle accelerators and magnetic resonance and imaging (MRI) machines. Superconductivity has been employed or proposed for use in a variety of applications and sectors, including the energy, transportation, industrial, medical and defense sectors. High temperature superconducting (HTS) wire is the key enabler that makes devices for the electric power system more efficient and resilient than conventional solutions.

THE BENEFITS OF HIGH-TEMPERATURE SUPERCONDUCTIVITY

The International Energy Agency's Technology Collaborative Program on High Temperature Superconductivity (HTS TCP) monitors includes electric transmission and distribution, energy storage, wind energy, all electric aircraft and motors. The thought leadership of the HTS TCP has helped to realize several important projects.



A picture of SuperOx's patented superconducting tape that was deployed in Russia's first SFCL at United Energy Company's JSC Mnevniki Substation. *Image Courtesy of SuperOx.*

A picture of Russia's first commercially operational SFCL at United Energy Company's JSC Mnevniki Substation in Russia. *Image Courtesy of SuperOx.*

Electric Transmission and Distribution

Load growth in urban and suburban regions requires utility companies to make long-range plans for increasing the capacity of the AC circuits that serve that load. It is well known that HTS cables can carry much larger levels of power than conventional cables for the same underground cross-section and right-of-way (ROW). Alternatively, an HTS cable can provide the same level power, but at a much lower voltage. In some cases, both of these features may be realized in a single project. In addition, many of the world's utilities are coping with increasing fault (short-circuit) currents, possibly requiring new substation circuit breakers. An HTS fault current limiter (FCL) can help manage increasing fault currents more cost- effectively and reduce losses by at least 50% in solid-state FCLs and at least 90% in fault-current- limiting reactors.

Energy Storage

Energy storage can increase the penetration of renewable resources and improve power quality. Superconducting Magnetic Energy Storage (SMES) has several advantages over other storage technologies, including rapid response times, nearly infinite charge/discharge cycles without degradation, and very high round trip efficiency.

Wind energy

HTS-based wind turbines have the potential to generate the same amount of power with roughly half the size and weight of conventional designs, needing less rare earth metals and making installation easier.

Motors

Electric motors account for almost two-thirds of all electric energy consumption in the United States and other developed countries. Superconducting motors have the potential to reduce losses by 50% and can be less than half the size and weight of conventional designs, which can improve the propulsion and maneuverability of transportation vehicles.

All-Electric Aircraft

The use of lightweight HTS could lead to ecofriendly, exceptionally quiet, and highly energy efficient electric planes. Beneficial application of HTS technology is expected in the fields of power generation, power distribution and forming, and propulsion. In addition, auxiliary devices might be replaced by electric HTS-based solutions.

Beyond electric systems, HTS can improve ship degaussing, the process of decreasing or eliminating a remnant magnetic field to obscure ship radar signatures and avoid enemy detection. AMSC will deliver HTS degaussing systems for future U.S. Navy San Antonio class amphibious transport dock ships, beginning with LPD 30. *Image Courtesy of HII/Ingalls Shipbuilding*

REMAINING CHALLENGES

Over the past few decades, significant efforts have been made worldwide on research, development, and field demonstration of applied HTS devices for the power sector. As a result of these activities, several HTS based devices, specifically HTS cables and FCLs, are being energized in utility grids as permanent solutions to electricity delivery challenges. However, other applications are still lagging in deployment into commercial installations. The transition of HTS applications to widespread market maturity faces several challenges.

Several general examples include:

- Manufacturing: There are still manufacturing problems regarding the optimal architecture and production processes for specific applications. For example, it is still difficult to grow the HTS to achieve higher critical current values, as well as choosing the correct buffer layers, without introducing excessive residual or thermal stresses for long lengths.
- Reliability: End users are generally unfamiliar with the materials used in HTS devices and cryogenic systems. Data that prove undiminished product performance of HTS components over 30 to 40 years are not available yet.
- Market: Uncertainty exists for total cost of ownership, maintenance, cost and availability of spare parts from suppliers in a relatively nascent market.
- Economics: The costs of HTS-enabled devices are still significantly higher than conventional, copper based counterparts because the sophisticated production processes, current low yields, and limited throughput of HTS tape manufacturing processes have kept costs high – there are still no observed effects from economies of scale.

Several specific examples of barriers to greater deployment of cable systems includes potential issues with factory testing and cryogenic and vacuum systems.

Factory Testing: Underground cable is shipped from the manufacturing plant on large reels. The capacity of a shipping reel is limited to between 0.5 and 1 km, typically, depending on cable design and transportation methods. Factory acceptance testing for voltage integrity of electrical insulation is necessary for 100% of all reels shipped to the project site. Otherwise, a reel with potential insulation defects may produce failure in the field when first energized. Location of the failed section, removal, reinstallation and recommissioning is a costly and time-consuming process. Projects involving more than a very few reels of untested cable have a statistically high probability of encountering a faulty reel due to the inherent variability in any manufacturing process. Acceptance testing is therefore a standardized step in the manufacture of conventional cable. However, at present, there is no means to do the same for an HTS cable because the insulation of present day HTS cables requires wetting paper tapes with a liquid cryogen. Factory testing would require immersing an entire shipping reel (weighing tens of tons) in the liquid cryogen – a clear impracticality.

There are potentially two approaches to overcome the acceptance testing barrier. The preferred approach would be to develop and test a solid dielectric similar to conventional cables (i.e., extrudable), capable of performing at cryogenic temperatures but not requiring the reduced temperatures for its electrical insulating properties. The resulting cable could be factory tested with essentially the same methods as conventional cable. There is research in the U.S. underway to develop such a dielectric. Alternatively, it may be possible to develop standardized surrogate tests on cable samples from each reel, the results for which can be shown to apply to all of the cable on the reel with more than reasonable certainty.

Cryogenic and Vacuum Systems: The need for optimized and field-proven cryogenic systems for HTS cable installations presents another barrier. Cryogenic refrigeration is a well-established industry for many applications, but there are not available systems designed specifically for HTS cables. Economic studies suggest that the efficiencies of commercially available refrigerators is inadequate for utility applications. Available refrigerator sizes also are not optimal. Space limitations within the substation for refrigeration equipment, particularly in the dense urban locations most attractive for this application, may require innovative approaches, yet to be determined. These situations lead to uncertainties regarding system design and performance, operational characteristics, and maintenance procedures.

Additionally, the there is little or no precedent for mechanical equipment installed inside utility substations nor for the presence of non-utility maintenance personnel. Electric utilities are generally very conservative and risk-averse, preferring equipment that is well-proven for the application and operations that are entirely under their control. Achieving a higher penetration of HTS applications requires cryogenic systems that have been optimized and fully tested for longer-length underground HTS cable systems, as well as having operation and maintenance practices that are consistent with current electric utility industry standards.

154 kV SFCL in Gochang Korea. *Image courtesy of KEPCO.*

Purpose and Scope

The International Energy Agency's Technology Collaborative Program on High Temperature Superconductivity (HTS TCP) brings together key stakeholders to address the challenges of promoting the development and use of HTS technology in view of common interests. Particularly, the HTS TCP:

- Collaborates with electric utilities, governments, professional engineering organization and the RD&D community to confirm and communicate the potential benefits of HTS technology.
- Sponsors workshops, co-authors books and journal articles, exchanges information, introduces Executive Committee (ExCo) members' research facilities to other participants and guides the assessments.
- Develops position papers and strategic documents such as roadmaps and technical reports. Participants also ask experts from their countries to provide for input and to peer review draft reports. These activities help ensure consistency in the reporting and evaluate progress in the different considered fields.
- Provides expertise that can inform the evaluations and assessments performed by ExCo members.
- Interacts with other related IEA TCPs to leverage synergies and opportunities.
- Disseminates work at international meetings and workshops, and supports students, young engineers, and scientists who are learning about HTS applications in the power sector.
- Addresses and clarifies perceived risks and hurdles to introduce a disruptive technology into the conservative electric power industry.

Summary of 2020 Activities

While the pandemic changed the format of the TCPs ExCo meetings, it did not change the frequency. two Executive Committee meetings were held:

- ExCo meeting (via webinar) was held in September 2020
- ExCo meeting (via webinar) was held in March 2020

In 2020, the TCP received approval for another five-year extension (2021-2026) from IEA. The 2021- 2026 work plan will focus in two main areas: analysis of cross-cutting issues and communications and outreach with increased industry and government collaboration. The HTS Technology Collaborative Program (TCP) works to identify and assess the potential applications and benefits of superconductivity, as well as what technical, economic and regulatory barriers must be overcome to achieve them. Through its contracting parties, the HTS TCP develops technical communications documents that provide information for a range of stakeholders.

In the 2021-2026 period, the HTS TCP will focus on activities that could accelerate the market adoption of superconducting applications. The rationale for this is that the technology readiness level of several HTS applications is at a point where it is technically capable to be included in electric system operation, for instance. The HTS TCP will demonstrate to key stakeholders that existing HTS technologies are technically and economically viable in a number of electric power and other related application areas.

The TCP also started to undertake the development of an Application Readiness Map. These maps describe the technology readiness levels of HTS devices and their underlying technologies, such as wire and cryogenics, for use in electric power applications.

The development of this application map is motivated by the need to clearly communicate the readiness of HTS applications to policy makers and industry executives and will take into account the TCP's current quantitative analysis of various energy-related benefits of HTS technology.

The readiness map as a way to illustrate the technology readiness levels (TRL) over time of HTS applications in various sectors. Examples of sectors that HTS is, or can be, used in include energy delivery, energy supply, transportation, medicine, and industrial processes. The sector this document focuses on is in energy delivery, whose applications can be further broken down into transmission, substation and distribution. The TCP began developing TRL levels of various transmission, substation and distribution applications in the energy delivery sector. For each of the applications, the TRL for today and future were determined by using the input of industry experts. Factors influencing technology readiness include:

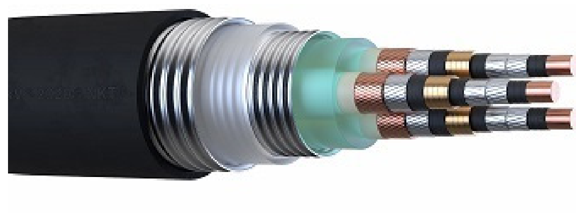
- Underlying scientific/engineering maturity (e.g., HTS wire design; cabling technology)
- Potential for ongoing R&D of component technologies (e.g., existing or planned research activities; institutional support; etc.)
- Maturity of component subsystems common to other applications (e.g., cryogenic systems)
- Specific application readiness (e.g., maturity of HTS AC cable design)
- Education of developers as to customer needs

Project Updates

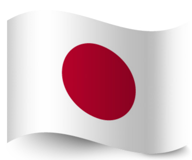
Around the world, projects are demonstrating the technical feasibility of electric power equipment incorporating HTS tapes. The text below highlights several project examples from IEA HTS TCP Member Countries.

GERMANY

The SuperLink project is now underway to develop a prototype of a superconducting power cable for installation in Munich, Germany. The planned 12 km underground power link is expected to be the longest superconducting power cable solution in the world. The SuperLink design has a power rating of 500 MW and a voltage level of 110 kV, which is stated for installation between two substations those are the main Menzing substation in the west of the city and the load center Munich-South using existing ducts to keep the construction work at a minimum.



The 12 km underground power link is expected to be the longest superconducting power cable solution in the world. *Image courtesy of NKT.*



JAPAN

The Railway Technical Research Institute (RTRI) conducted a disconnection test and a power-on test of a superconducting power transmission system using actual vehicles running on a railway that supplies power at 600 V DC. This is the first demonstration in the world. RTRI also announced they had conducted power-on and system disconnection tests in the commercial line's power supply (Chuo Main Line, 1500 V DC) as part of an application test for the commercialization of a superconducting power transmission system.

The MIRAI Program in Japan, is developing superconducting joints for persistent current nuclear magnetic resonance devices and ultra-low resistive joints for elongation of DC superconducting feeder cables for railway systems. In the DC feeder cable ultra-low resistance joint project, the first prototype of the intermediate joint between HTS feeder cables was demonstrated.

KOREA

In Korea, the KEPCO sponsored Shingal-Heungdeok triple-core HTS power cable project is ready for comamercial operation, having completed commissioning tests. KEPCO has been planning to install a 2 km long 23 kV/60 MVA triaxial HTS power cable to connect the Munsan and Seonyu substations.

A team of university researchers developed a superconducting coil for 10MW wind turbines, which can potentially cut down turbine weight by one-third. The Korean Electric Power Research Institute announced that a research team from Changwon National University has developed a 10MW superconducting coil for large offshore wind turbines. The technology will overcome the limitations of conventional rotary machines and will be used not only in large-scale wind power generation, but also in ship propulsion.

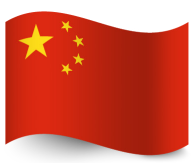
Site installation of a KEPCO's 23 kV HTS cable system in Korea. *Image courtesy of KEPCO.*

UNITED STATES

The U.S. Department of Energy (DOE) selected GE Research to receive up to $20.3 million to build and test a scaled prototype of their generator on a wind turbine. The project has the potential to result in a design that is up to 50% lighter while reducing the cost of wind generation by up to 10%.

The first phase of an HTS cable is being constructed in ComEd's utility service territory in Chicago, Illinois, USA to enable a more resilient grid. This project is starting with the testing and validation of 30 meter section of cable before it is used to connect two or more substations in a real grid application.

These project updates are examples from other countries and regions.



CHINA

Shanghai Electric Cable Research Institute is developing a 35kV 2.2kA HTS cable project in Shanghai. It is a 3 in 1 type cable that is about 1.2km long. The route construction started on April 30th, 2020. The project will be energized in 2021.

The Chinese Academy of Sciences and Electric Power Research Institute is working on integrating an HTS cable and liquefied natural gas transportation into a single pipeline. HTS DC cables are a promising solution for large-scale power transmission over long-distances. However, the refrigeration system for the HTS cable is challenging. Considering that liquified natural gas is used more widely, the Chinese organization is designing, fabricating and testing a new energy transportation system that is a 10 kV/1 kA energy pipeline.

Guangdong Grid Company of China's Southern Power Grid is leading a project to develop a 160 kV/1 kA resistive type direct current superconducting fault current limiter. The project is starting as a laboratory prototype and when scaled up it will help to improve the safety of the HVDC network by reducing the fault current levels in the grid.

EUROPE

The FastGrid project is developing a cost-effective fault current limiter using advanced superconducting tapes for future high voltage direct current grids. There is strong interest for HVDC SFCL, but today's tape is not suitable in terms of cost. In addition, the enhancement of reliability under high voltage is required. The project is working on significant advances of the attractiveness of SFCLs by improving REBCO tapes, especially in their current limitation mode.

RUSSIA

The first 220 kV SFCL at 220/20 kV substation in Moscow was energized in December 2019 and successfully limited faults and continuously operated normally after several events in October 2020.

Working Arrangement

In 2020, there were two operating agents (OAs) supporting the HTS TCP, one based in the United States and one in Japan. They are managed by the ExCo, whose duties are specified in a contract with the OAs and include provision of technical and support services. The HTS TCP operation is supported by a combination of cost-, task-, and knowledge sharing. ExCo members cover their travel expenses to attend ExCo meetings and bear all the costs incurred in conducting task activities, such as report writing and travel to meetings and workshops.

The ExCo Chairman, vice-chairman and operating agents prepare an annual work plan and associated annual budget for the calendar year, which are submitted for approval by the ExCo. The expenses associated with the operation of the HTS IA ExCo and the annual work plan, including the operating agent's time and travel and other joint costs of the ExCo, are met from a Common Fund to which all HTS TCP members contribute. No changes to either the working arrangement or current structure fee are anticipated. In FY 2017 the fee structure had been modified based on the GDP of the member countries. The HTS TCP Common Fund is financially secure and has had a surplus for the past several years.

Membership in the ExCo remained the same since the previous annual report, but the ExCo is making a concerted effort to increase membership. The TCP has a strong policy relevance within each of its member countries. It provides unbiased technical expertise to policy makers and contributes to documents in the public domain by gathering data for publication. For instance, the HTS TCP maintains this relevance through various channels such as:

- Government officials from Japan and U.S. participate in the ExCo
- One of the German delegates advises the responsible persons in its government
- The Italian representative is supporting the Ministry of Economic Development
- Korea is represented by its electric power company which has a vigorous HTS RD&D program that is among the world's leaders

ALIGNMENT WITH IEA MISSION

The HTS TCP's strategy is aligned with key components of the IEA mission. These include energy efficiency, energy security, system integration of renewables and engaging stakeholders around the world.

- **Energy Efficiency:** Contributes to several applications with improved efficiency over conventional systems in electricity grids, industry and transportation. Examples include, components for AC and DC grids such as cables, transformers, energy storage systems, busbars, but also induction heaters and in future transportation applications for all-electric aircraft, high-speed train, and electric ships.
- **Energy Security:** Supports energy security focusing on HTS-based technologies - primarily fault current limiters and superconducting magnetic energy storage systems (SMES), that can help to enhance grid reliability and resilience.
- **System Integration of Renewables:** Provides research, analysis and information related to the use of HTS components - such as high-capacity power cables, fault current limiters, high-efficiency generators for offshore wind turbines, energy storage, and innovative transformers–able to facilitate increased renewable generation integration in electric grids.

- Engagement Worldwide
  - Actively engages groups of stakeholders, such as electric utilities, governments, the professional engineering community and the RD&D community, worldwide.
  - Connects with other IEA TCPs such as the International Smart Grid Action Network and Wind TCP.

FUTURE ACTIVITIES

Several activities that could be undertaken in the next year include:

- Expanding on the HTS Application Readiness roadmap that describes the market readiness level for where the HTS industry is now and in the future in the electric sector.
- Organizing a joint TCPs workshop (e.g., Hydrogen TCP, Fusion TCP, or other related TCPs) to share experience and synergies of using HTS technologies
- Bridging the gap between technology developers and electric utility system planners by developing technical materials to explain how the systems work and provide best practices and lessons learned from other projects.
- Increase communication and active engagement with relevant industry sectors where appropriate, extending the distribution of policy recommendations to a wider industry audience.
- Continue to document environmental benefits from the future deployment of HTS power equipment.
- Collectively work to build new HTS application projects to help realize environmental benefits.
- Fulfill all tasks to comply with the TCP modernization requirements indicated by IEA Office of Legal Council
- Organizing at least two executive committee meetings in 2021 and co-locating other industry meetings to leverage expertise from other experts.

Superconducting cable terminations at the Asahi Substation in Japan. *Image courtesy of Steve Eckroad.*

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About the International Energy Agency

The IEA is an autonomous organization which works to ensure reliable, affordable and clean energy for its 29 member countries and beyond. The IEA has four main areas of focus: energy security, economic development, environmental awareness and engagement worldwide. Founded in 1974, the IEA was initially designed to help countries coordinate a collective response to major disruptions in the supply of oil such as the crisis of 1973–1974. While this remains a key aspect of its work, the IEA has evolved and expanded. It is at the heart of global dialogue on energy, providing authoritative statistics and analysis.

As an autonomous organization, the IEA examines the full spectrum of energy issues and advocates policies that will enhance the reliability, affordability and sustainability of energy in its 29 member countries and beyond.

The four main areas of IEA focus are:

- Energy security: Promoting diversity, efficiency and flexibility within all energy sectors;
- Economic development: Ensuring the stable supply of energy to IEA member countries and promoting free markets to foster economic growth and eliminate energy poverty;
- Environmental awareness: Enhancing international knowledge of options for tackling climate change; and
- Engagement worldwide: Working closely with non-member countries, especially major producers and consumers, to find solutions to shared energy and environmental concerns.

ENERGY TECHNOLOGY INITIATIVES

The IEA energy technology network is an ever-expanding, co-operative group of more than 6,000 experts that support and encourage global technology collaboration. At the core of the IEA energy technology network are a number of independent, multilateral energy technology initiatives – the IEA Technology Collaboration Programmes (TCPs).

Through these TCPs, of which there are currently more than forty including 4E, experts from governments, industries, businesses, and international and non-governmental organizations from both IEA member and non-member countries unite to address common technology challenges and share the results of their work. Each TCP has a unique scope and range of activities.

Further information is available at: ***http://www.iea.org/tcp***

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