Concentrating Solar Technology Policy Should Encourage High Temperatures and Modularity to Enable Spillovers

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Thermal energy from concentrating solar thermal technologies (CST) may contribute to decarbonize applications from heating and cooling, desalination, power generation to commodities such as aluminium, hydrogen, ammonia or sustainable aviation fuels (SAF). So far, successful commercial-scale CST projects are restricted to solar industrial process heat (SIPH) and concentrating solar power (CSP) generation and, at least for the latter, depend on support from public policies that have been stagnating for years. As they are technologically similar, spillovers between SIPH or CSP and other emerging CST could accelerate the commercialisation across use cases, while maximizing the impact of the scarce support. Here, we review the technical potential for cross-fertilization between different CST applications and the ability of the current support policy regime to enable this potential. Using working temperature as the key variable, we identify different clusters of current and emerging CST technologies. Low-temperature CST (<600°C) applications for heating & cooling, or desalination already profit from the significant progress made in line focussing CSP over the last 15 years. A newly emerging cluster of high-temperature CST (>600°C) for solar chemistry and high-grade process heat has significant leverage for spillovers with point focussing solar tower third generation CSP currently under development. To realize these spillovers, however, CSP policy designs would need to prioritize innovation for high working temperature and modular plant design, capable of utilizing and providing different levels of heat in and outputs. This would enable synergies across applications and scales by incentivising application of the same components in multiple sectors.

1. Introduction

The complete decarbonization of the economy is one of the great challenges of our time. While the power sector is leading the way, other sectors such as industrial processes and aviation lag behind and need to deploy pre-commercial technologies at very large scale in the next 30 years to reach climate neutrality [1]. To start bending these emission curves, theoretical concepts need to be developed into bankable projects. First-of-a-kind projects are often expensive and take a long time to complete, but they provide valuable lessons for later projects, enabling faster construction and lower cost. Unfortunately, to get on emission reduction trajectories in line with the Paris agreement, the time for experimentation is running out: large-scale emissions reductions and deployment of non-emitting solutions are needed fast.

Solar energy is the most abundant form of renewable energy on earth. In the power sector, solar technologies are already deployed at large scale. Public policies were instrumental for commercializing both Photovoltaics (PV) [2] and concentrating solar power (CSP) systems [3]. For the latter, significant experience in industry, support policies, project development and operations and maintenance has been accumulated [4], although overall deployment remains much smaller than for PV and new projects still depend on policy support [5]. Meanwhile, academic publications and several pilot stations show that thermal energy from concentrating solar thermal technologies (CST) is also a plausible solution for the decarbonization of other sectors and applications. To commercialize them, further policy intervention to accelerate innovation and diffusion will be required. In the interest of fast market uptake, this also poses the question if and how other sectors that may use CST solutions for decarbonization can profit from the experience gathered in the technology, industry or policy of CSP generation spilling over to other CST applications. Further, although CSP has progressed a lot in recent years, the availability of cheap solar PV has had adverse effects on the deployment of new CSP projects and policies [5]. A potential route to reinvigorate the CSP market could thus be learning effects from more dynamic CST applications allowing for cost reductions and making deployment more attractive. Here, we investigate the interlinkages between current and suggested CST technologies and map potential synergies for their deployment and policy pathways.

2. Method

All concentrating solar thermal technologies (CST) rely on mirrors to collect heat in a receiver. Thus, they may share many of the solar-specific components or use similar technology for heat transfer, storage or conversion. On the other hand, the working temperature varies by application and thus plays a key role for the differentiation of CST. Generally speaking, higher temperatures are associated with better thermodynamic efficiency and enable novel use-cases, however, higher temperatures pose significant material and engineering challenges to successfully operate a commercial plant for decades with minimal maintenance needs. In this paper, we first identify current and possible medium-future CST applications and their required temperatures based on the task descriptions of SolarPACES, an international innovation program aimed at commercializing CST. We take the six tasks of SolarPACES as the starting point to characterize the requirements of these applications in terms of their similarities and differences with technology, industry and policy of CSP, that we analyze based on the CSP.guru database [6]. We distinguish fully commercialized from developing technologies and identify synergies and potential spillovers. For technologies that have not reached commercial breakthrough, we rely on academic publications and reports on current pilot and pre-commercial plants to describe their technical profile and identify potential synergies and spillovers with current CSP industry and technology as well as future CSP technologies, but also highlight the risk of locking-out applications if deployment focusses on technologies that are not compatible.

Second, we review the literature on state-of the art of deployment policies for CST in the light of incentivizing technical interrelatedness and promotion of CST innovation across sectors [7-9].

3. Results

3.1 A Spillover Map of Concentrating Solar Technologies

3.1.1 Cheap and Dispatchable Power

SolarPACES task one is concerned with concentrating solar power (CSP) systems often also called solar thermal electricity (STE). CSP is by far the most advanced and successful CST technology. Most commercial scale projects use parabolic troughs with thermal oil at just below 400°C [6]. This technology has existed since the 1980s and has matured significantly and advanced in materials and manufacturing as well as operations and maintenance have been made [4, 5]. More recently molten salt based CSP systems, especially in towers with thermal energy storage (TES) reached temperatures as high as 565°C. This coincided with an increased focus on dispatchable generation from storage [10, 11], and resulted in higher load factors in new commercial-scale projects and the disappearance of CSP designs that do not easily include large scale storage (namely direct steam generation and solar dishes). Today, virtually all new CSP plants include large multi-hour (molten salt) TES. Currently, not only towers but also both parabolic trough and linear Fresnel plants using molten salt as heat transfer medium are researched and first projects are under construction.

In the coming decade, significant cost reductions are expected from achieving higher working temperatures in third generation CSP plants [12-14]. For these plants, new high-temperature materials are needed, and several demonstration plants are under construction and their receiver technology is one of the key topics in CSP research. Spillovers between second and third CSP generation are expected in so far as they both use central receiver tower designs (see table 2, for 3rd Generation plants). However, the *temperature* of CSP systems is of secondary concern for power generation: the primary goal is to reduce the *cost* of power production. Therefore, another route for cost reduction of solar power plants is through *hybridization* with cheap solar PV generation [15, 16]. This fundamentally changes the character of the CSP plant by adding an additional power source, namely cheap power from solar PV to the CSP plant, either to add low-cost PV electricity to the station output [17], or to increase the operating temperature of the CSP power station [16].

A third trend is the development of stand-alone molten-salt storage and other thermal energy storage system. So called Carnot batteries could play a large role for meeting residual load in high-RES scenarios [18] but may also find application for other uses [19]. These facilities may leave out the solar field altogether and use other heat sources such as waste heat or electric resistance heating to warm up the storage medium. This opens up the possibility to also use CST technologies countries with low DNI [20] but does foreseeably not help to improve the solar components of CST plants. On the contrary, currently a large number of start-ups, often with roots in the CSP industry, work on their own designs and novel products with a wide variety of materials, with only some foreseeing the future inclusion of solar fields. Table 1 shows a non-exhaustive list of TES start-ups. They are very different in the materials and geared at diverging sectors and end products. We observe a similar split as in CSP technologies: while some go for lower grade heat for district heating or steam for industry, other including Kraftblock and 1414-degrees emphasize the promise of reaching storage temperatures well above 1000℃. The products also differ across companies and approaches, the palette includes not only power but also different grades of heat. Some, but not all, of the TES startups still advertise the capability to use heat from a solar field to co-charge the thermal storage.

TABLE 1. Technological and business model diversity in start-up in standalone thermal energy storage, information based on company websites and presentations [21-26].

Company	Input	Output	Maturity	Heat Storage Medium	Storage Temperature Duration
Azelio	Power or CST	Power (29%) and heat (65℃) 61%	Mass production planned for 2021	Aluminum: Phase Change Material	<600℃/ 13 h
Malta	Power	Power	Demo plant by 2025	Molten Salt and Cryogenic liquid	565 ℃/10-200 h
Energy NEST	Heat, or CST	Heat	First commercial orders	Concrete	380 ℃
Kraftblock	Heat, CST, Power	Power or heat	unknown	Unknown granulate	1300 ℃ 4-60MWh
Lumenion	Power	25% power 70% heat (@100℃)	First pilot	Steel	650℃
1414-degrees	Power, CST	Power, heat	Demo planned	Molten Silica	1414 ℃
Brenmiller Energy	Power, heat, CST	Heat, power	First commercial orders	Crushed rocks	750 ℃

3.1.2 Low and medium grade heat (below 400-500 C): Heating, cooling and solar for industrial process heat (SIPH)

The energy need for heating and cooling is a very large and a potentially important application for renewable solar thermal energy [27]. There is a whole other IEA program on Solar heating and cooling (www.iea-shc.org), that has recently started working together with SolarPACES because CST are a great option to use for solar for industrial process heat (SIPH), but CST may also be used for a range of heating applications including space, water or district heating that require mostly “boiling” water. Indeed, instead of driving a turbine the heat collected in a CST solar field can also be used to deliver heat, for example in the form of steam. Most industrial heat needs are in the relatively low-temperature range of 100-400℃ [28]. The suitability of CST for a given industry also depends on seasonal daily heat demand [29]. Parabolic trough and Fresnel collectors can be easily adapted and used for SIPH applications, and several projects have been realized. A database run by IEA SHC lists 58 SIPH projects using parabolic trough collectors and 17 using Fresnel designs (www.ship-plants.info, accessed 19. August 2021).

Two special cases of medium-grade heat delivered from CST that have seen some large commercial projects are enhanced oil recovery (EOR), which uses steam to lower the carbon footprint of oil extraction, and integrated solar combined cycle power plants (ISCC), which add a solar field to save fossil fuel inputs by utilizing solar heat to run their turbine. For both applications, first commercial-scale plants that used CSP-like solar fields with parabolic through or solar towers have been built, but neither technology has achieved large-scale commercial deployment, although the first ISCCs have been operational for over a decade. At the end of 2020 Glasspoint Solar the industry leader in EOR undertaking a by far largest 1 GWth EOR project in Oman went into liquidation[30], casting in doubt any additional EOR projects, as the oil-and-gas industry experiences fluctuating prices and an uncertain future.

3.1.3 Solar water treatment: desalination, detoxification

Many older CSP plants have relied on wet-cooling and cleaning and have a significant water consumption, even today most of the plants use a steam-turbine. This may change thanks to dry cooling and advanced power cycles. But CSP plants may also help to produce clean water. SolarPACES task VI - *Solar water treatment: desalination, detoxification* is somewhat of a special case of SIPH. The energy demand for water treatment like desalination is very large in arid countries with lots of solar irradiance. Different desalination technologies and integration pathways with CST exist. Blanco, Alarcón [31] review these technologies and the potential to integrate their processes into a CSP plant. They find that the cost baseline to beat is reverse osmosis using the cheapest available power from the grid. The alternative is to use solar thermal heat for multi-stage flash distillation (MSF) or multiple-effect distillation (MED) at a coastal location where solar resource may be not optimal. However, as the temperature needed for desalinations is not very high CSP+D presents a great case for combined heat and power and desalination may be able to rely on waste-heat entirely for third generation solar towers plants [32]. Other design propose to use much smaller parabolic trough type collectors to collect primary heat for water purification [33]. So far, the market prospects seem to be dim; and we know of no commercial desalination projects using CST [34], nor of any deployment support or literature on that.

3.1.4 Solar Chemistry and other high temperature applications

SolarPACES TASK II investigates solar chemistry and thermochemical energy storage [35]. With the complete phase-out of fossil-fuels there is a lot of commodities and energy carriers that need to be provisioned in a carbon neutral way. Solar chemistry follows the key idea to drive endothermic reactions at high temperatures through CST. Apart from high temperature receivers, this also needs technology to handle the material streams of ore or working gases. The most long-term vision is to be able to produce fuels from water and CO2 and thus effectively close the fossil fuel carbon cycle [36]. Thermochemical storage could also be a good option to replace current molten-salt storage to be able to provide dispatchable and very hot process heat and power. To be able to produce energy carriers such as green hydrogen and sustainable aviation fuels (SAF) process with temperature above 700°C up to 1500°C are needed. No commercial scale CST project has reached these temperatures [37]. Thus, solar chemistry remains in its infancy, but is thought to be able to, for example, provide all of global jet-fuel needs [38] or hydrogen [39]. A minority of industry applications, investigated in SolarPACES TASK IV, also require temperatures of more than 1000 °C [29].

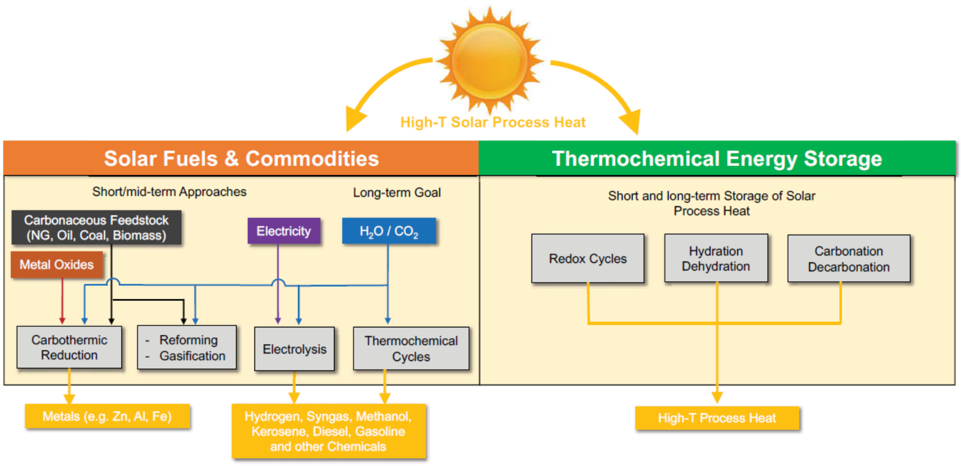

Figure 1: Applications for high-grade solar process heat. Picture from [40].

Table 2 highlights that in terms of concrete projects, all CST projects working above the upper boundary of molten salt are only in the demo or pilot phase and reach temperatures between 600-1000 °C. Processes and receivers reaching even higher temperatures are not yet available. There is a large variety of heat transfer fluids, but all start-ups are relying on a heliostat field and a central-receiver tower. Therefore, they may be able to greatly profit from progress in commercial scale solar tower CSP projects. For example, a common learning seems to be to rely on smaller unit size of 200KW in the case of 24/7 solar or 5MW in Heliogen's case. We observe that the commercialization of high-temperature applications is closely related to the development of third generation CSP for power production.

TABLE 2. No exhaustive list of Start-up and demo plants in high-temperature CST. If two temperatures are listed, the first is current design, and the second future ambitions. Sources from: [41-46]

Company	Heat transfer fluid	Solar field	Receiver temperature	Output	Maturity
Heliogen	Not known	Tower	600 -1500 °C	Power, Heat	Demo, Lab
Synhelion	-	Tower	800-1500 °C	Blue-H_2, SAF	Pilot, Lab
HiFlex	Particles	Tower	1000 °C	Power, Pasta	Pilot
Vast Solar	Sodium	Tower	565-900 °C	Power	Demo, Lab
24/7 Solar	Hot air	Tower	970 °C	Power, heat	Pilot
Sandia G3P3	Particles	Tower	775°C	Power	Pilot

3.1.5 Combined heat and power and plant modularity

Taking a step back reveals that concentrating solar technologies are today embedded in a landscape of technological solutions utilizing, storing and converting different forms of heat for several different potential products. In this sense, a CST solar field can be understood as only one module in a larger (renewable) thermal energy plant. CSP is thus only one specific case taking solar heat only and converting it to (dispatchable) power only. Indeed, from a technical perspective a CST plant may use additional heat sources, including curtailed electricity or waste heat and deliver several products including power, different grades of heat or even chemical products – different CST applications may converge in one plant. If the right use cases and business models can be identified and combined, this should allow for cost synergies for example if both low-cost heat and power or power and water are needed.

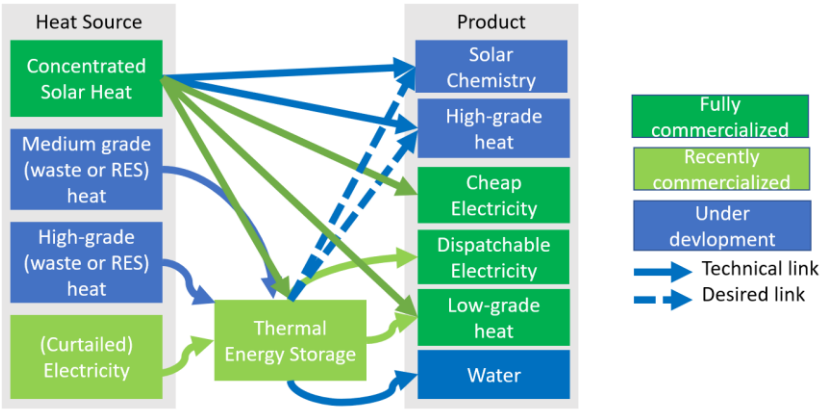

Figure 2: Systematic embedding of concentrating solar technologies as a link of heat resources and products. Blue are potential links that are not yet commercialized. Multiple links may be exploited in a combined heat and power plant.

Indeed, solar desalination can be a by-product of third generation CSP plants. Similarly, using both the output of heat and power from CSP plants for high-efficiency hydrolysis as suggested by Heliogen goes in the same direction by proposing high-temperature hydrolysis powered by CSP and solar heat [47]. Other use cases are envisaged combining both high-temperature process-heat and power [43].

3.2. Spillovers in CST components, industry and project development

Technologically, the solar components of CST technologies are closely related. They all rely on a solar field of mirrors but may have different receivers or use the collected heat in a different way. Synthesizing the results of the previous section, Figure 3 shows three large areas of potential spillovers in terms of parts of a plant and other applications. Many parts of a line-focusing CSP plant including the solar field, receiver and thermal storage may be almost directly used to provide heat for SIPH or Desalination. Carnot batteries on the other hand, are somewhat different as they are essentially a CSP plant without the solar field. They are thus by definition not a CST technology per-se but included here because they are closely technologically related and may share several parts, including the turbine. Nevertheless, as table 1 shows, future designs are not necessarily compatible with the requirements of third generation CSP plant (table 2) and only progress in some Carnot battery designs may also be applicable for future CSP plants. A third field of potential overlap is in the heliostat field technology of current and emerging central receiver CST, that may also inform the solar field needed for solar chemistry applications in the future. The materials for future high-temperature applications could be shared in the future.

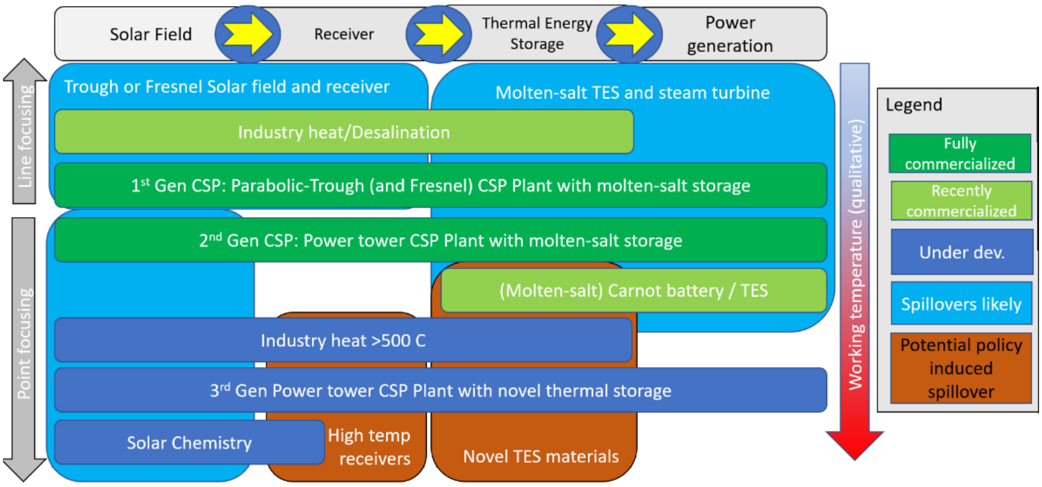

Figure 3: Potential spillovers between CSP and other CST technologies. Figure adapted from [10].

SolarPACES TASK III - *Solar Technology and Advanced Applications* already takes an integrated perspective in viewing solar receiver technology as a continuum and aim to establish best practices for quality control and standardize emerging receiver designs and heat-transfer and storage solutions [48]. In a similar vein, SolarPACES Task V - *Solar Resource for High Penetration and Large Scale Applications* provides a common resource for all kinds of CST projects [49]. Independent of the application, understanding the resource and having high quality models available is core for commercial success. Advances in quality control of solar components and solar resource assessment, project finance etc. that were made in the context of CSP projects in the last 15 years will also be directly available for developing other kinds of CST projects. All three clusters may profit from knowledge in mirror manufacturing, heat collection and transfer, as well as from policy and regulatory learning made in CSP projects, but also require specific innovations of their own.

As there is not yet a market for some emerging CST technologies, they also do not have a strong industry of their own. Indeed, all companies in the *market advisory board* of SolarPACES in 2021 are mainly active in CSP. As there are no commercial-scale projects yet that produce green hydrogen via solar steam reforming or use direct air capture or other emerging applications. Similarly, solar desalination only exists in the lab. However, companies already understand the potential of modularity and the overlap of CST technologies. For example, US based startup Heliogen offers different kinds of products including heat, power, and hydrogen [47, 50].

3.3. The absence of a unified CST deployment policy

Even though there is a large technical potential for double use of CST across sectors or joint technology development pathways, these synergies between CST across sectors has so far received little attention in the policy literature. Cardoso, Marcelo [51] describe steps to integrate CST R&D funding across European funding and several promising projects are under way. But so far, this integrated view has not translated into the policy arena. Indeed, where a search for "CST Policy" returns no results in google scholar, we found different papers investigate recent advances in CSP policy. The literature emphasizes on the value of dispatchable power [7, 8, 52] to regain competitiveness vis-à-vis photovoltaics, but still largely disregards the potential of spillovers from other applications and the potential for cost-reduction by multi-use plants. Kiefer and del Río [53], as a notable exception, highlight the potential for experimentation with CSP technologies in adjacent sectors as a potential driver for CSP in the European Union but remain undecided on how to exploit this driver with public policies.

As we have seen, the entire commercial-scale deployment of CSP plants, which constitute most of all CST plants to date, have been enabled by public policies, without which they would not have been successfully commercialized. Now, different other uses stand to gain from the tacit knowledge and project development experience made in CSP in the last one and a half decades. The general lack of new large-scale policy interventions for deploying CSP plants thus also impairs future success of other CST applications. Similar R&D and deployment policies may be used to create markets for other CST technologies, too. For example, for industry heat from SIPH funding and R&D programs in several countries are available and have also led to some commercial projects. Also, there is a strong case for stand-alone TES systems. Long duration energy storage (LDES) has a potentially large role to play to reduce cost in variable renewables rich power systems once they get very cheap [54]. This justifies having auctions for storage and several places already explore this option, so far with very limited deployment of standalone TES systems.

4. Discussion, Conclusion and policy recommendations - Towards a unified CST Policy

In this paper we showed that CST technologies have potential applications in many major emitting sectors including power generation, different grades of industry heat, sustainable energy carriers for different applications, as well as water desalination for agriculture and space heating and cooling. Figure 4 shows that the technology development was closely related and may continue to do so. Especially, first and second-generation CSP, and the associated molten-salt storage are may inform two large clusters of CST technologies. We find that significant spillovers in terms of industry and technology from the development of CSP already help for applications of CST in SIPH applications below 500°C that already use solar fields that are closely technologically related to current state-of-the-art CSP plants. Similarly, emerging thermal energy technologies build on molten-salt technologies from CSP.

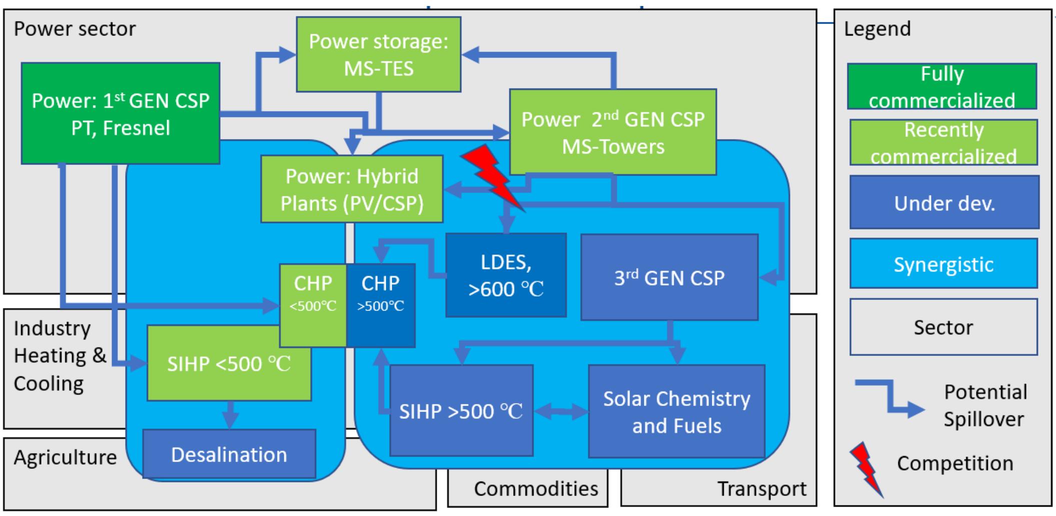

Figure 4: Spillovers between current and emerging CST technologies

The commercialization of 3rd generation CSP is closely related to the development of high temperature heat applications for industry decarbonization or sustainable aviation fuel. Those pilots under development follow the central receiver tower design and can thus greatly profit from the experience in 2nd generation molten-salt CSP towers and their parts (especially Heliostats). Spillovers of either application breaking through, could aid the commercial success of the other, thus it makes sense to think their commercialization as two sides of the same coin. Companies with experience in tower-type CSP may be well suited to offer project development and components for emerging high-temperature industry heat and solar chemistry applications. However, the commercialization of CSP so far also highlights the role of targeted subsidies, that are currently absent for high-temperature CST applications. Especially, since CST is often not the only solution for a given problem, technology specific support is needed to build a high-temperature CST innovation system

While deployment of CSP is currently slow, there are several applications of CST technologies that hold promise for large scale deployment in the next decade. Novel TES designs and components and their potentially widespread deployment as grid-scale batteries could spell significant progress in the non-solar components of CSP plants. An emerging market of CST in SHIP may improve existing solar-field technology and lead to manufacturing improvements. Both TES and CST for SIHP have a significantly shorter path to market because of progress in CSP. If these new TES systems remain open for the combination with solar fields, a significant capacity growth of CST outside CSP could lead to improvements spilling back.

Creating support policies to further multiple goals or co-benefits is hard and may create unintended lock-ins of technologies that are cheap when auctioned and not those that are intended by the policy [55]. Still, to acknowledge the complex embedding with adjacent technologies CST policy could aim to maximize the likelihood of spillovers. For this policy makers need to clarify if they are also aiming to create co-benefits for the commercialization of low or high-temperature CST applications. Policy design may emphasize the following points to enable a cross-sectoral policy design aimed at improving several CST applications through spillovers:

- Encourage high working temperature in CST plants: this could be achieved through either a mandatory receiver outlet temperature of, e.g., more than 600°C excluding the eligibility of currently dominant molten-salt HTF, storage and receivers. A second option could be through paying a premium for higher working temperature similar to the premiums for dispatchability in current policy designs.
- Encourage the development of modular CST technologies suitable for multiple applications. Policies need to deal with the realities of CHP and encourage multiple forms of renewable or waste energy being fed into the same plant and multiple products coming out.
  - Remunerate Combined Heat and Power output: auctions for CSP or CST could include provisions for extra remuneration of waste-heat utilization to encourage double use
  - For TES and battery systems: include the possibility of charging from non-electricity energy sources, such as but not restricted to a CST solar field or waste-heat.
  - Clarify the role of combined heat and power input, add minimum quotas for energy that needs to come from a CST solar field.

If these points are considered, emerging CST technologies could find utilization along several other sources of energy and combining the output of heat and power and other products. This synergistic approach may also help to reduce overall policy cost and strengthen CST as one technology with multiple applications in different sectors.

Abbreviations

CHP	Combined Heat and Power
CSP	Concentrating Solar Power
CSP+D	Concentrating Solar Power with Desalination
CST	Concentrating Solar (Thermal) technologies[1]
EOR	Enhanced Oil Recovery
ISCC	Integrated Solar combined cycle
LDES	Long-duration energy storage
SAF	Sustainable Aviation Fuels
SIPH	Solar for industrial process heat
STE	Solar Thermal Electricity

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