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The Role of Innovation in Industry Product Deployment: Developing Thermal Energy Storage for Concentrated Solar Power

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Received: 2 May 2020; Accepted: 3 June 2020; Published: 8 June 2020

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Abstract: Industries with fast-developing technologies and knowledge-intensive business services rely on the development of scientific knowledge for their growth. This is also true in the renewable energy industry such as in concentrating solar power (CSP) plants, which have undergone intense development and expansion in the last two decades. Yet knowledge generation is not sufficient; its dissemination and internalization by the industry is indispensable for new product development. This paper contributes to providing empirical evidence on the known link between knowledge development and firm growth. In 10 years the cost of electricity produced through CSP has decreased five-fold. This decrease has only been possible due to innovation projects developed through a complex network of research and development (R&D) collaborations and intense investment, both public and (to a greater extent) private. The development and construction of pilot plants and demonstration facilities are shown to be key in maturing innovations for commercialization. This is an example of how the private sector is contributing to the decarbonisation of our energy system, contributing to the objectives of climate change mitigation.

Keywords: innovation; concentrated solar power; product deployment; pilot plant

1. Introduction

The importance of basic and applied research for economic growth is clear at national level and at firm-level [1]. This link of scientific knowledge is especially important for firms working with fast-developing technologies such as biotechnology, information and communications technology (ICT), and other high-tech sectors [2,3] and knowledge-intensive business services firms [4]. It is a fundamental instrument for increasing the penetration of renewable energy in a highly competitive technological market, as shown by some government initiatives such as Sunshot2020 which have driven fast-paced innovations through research funding.

This fact has been studied in depth in some renewable energy case studies such as the photovoltaic innovation system in China. Shubbak 2019 [5] highlights that research and development (R&D) activities were one of the main actors in shaping these innovation system dynamics. Another example in the clean-tech sector is the Danish company Vestas, which has relied on heavily investing on both internal and external R&D to become a wind turbine market leader, currently holding 27% of the worldwide offshore wind farm installations [6], filing over 780 patents—including the patent for the three-blade turbine design dominating the market—and exceeding the total wind power installed by General Electric or Siemens Wind Power.

The importance of corporate innovation is also highlighted in the literature [7] as a tool to improve productivity and to achieve higher potential output with lower manufacturing costs in a more efficient and environmentally friendly way [8] and as a tool for long-term business survival [9]. But corporate innovation is very costly, requiring massive fixed investments at the early stage of the product/process development to overcome the "valley of death". Literature highlights the fact that companies do not always have the needed skills inside/in-house in order to develop new innovative products/processes, and therefore collaboration with universities and research centers appears as an attractive tool [10,11]. Frameworks such as 'open innovation' have appeared to leverage an organization internal R&D by bringing external knowledge since an approach where companies "do it all themselves" to innovate is not possible for all or even difficult to sustain [12]. But partnership opportunities also include customers, suppliers, competitors and other stakeholders [13].

In addition to exploiting available knowledge, acquiring new knowledge, absorbing it, and finally internalizing it, is essential for advancing and developing new business opportunities as well as avoiding lock-in [14]. This knowledge advancement needs to identify knowledge gaps, having the capability and flexibility to integrate new with existing knowledge. Advancing knowledge is considered critically important for survival in an era of short product life cycles, advanced technological developments and considerable economic uncertainty [15]. Moreover, technological developments are considered crucial to increase the penetration of renewables in spite of erratic government policies and constant competition to reduce costs to substitute fossil fuels.

However, historically much more emphasis (and funding) is put on knowledge generation or value creation as the main driver for innovation, while the dissemination and absorption of this knowledge (value capturing) through actual industrial developments is presumed to follow effortlessly or required to be performed with private investment. For example, although US Federal spending on R&D has stayed more or less constant (with the research part slightly increasing above 0.4% of the US GDP (gross domestic product) since the 1970s), there has also been a steady decline in development (D) investments from almost 1% of the US GDP between the 1970–1990s to a current value below 0.3% for 2018 [12]. Although private investment complements these figures, the reality is that corporate R&D spending is generally meagre and reliant on public money. It seems widely accepted now that more attention should be given to how to take these new ideas, internalizing and utilizing them to develop new products and services.

Despite the fact that the link between knowledge and firm growth has been deeply studied in the literature, there is a clear lack of empirical evidence [16]. This paper contributes in filling this gap by presenting a case study which shows that innovation in a company working a rapidly growing market was the key point to achieve successful commercialization of new technologies.

2. Innovation in Concentrating Solar Power (CSP)

Concentrating solar power (CSP) or solar thermal energy (STE) uses reflective surfaces to concentrate the incident solar radiation to heat a heat transfer fluid (HTF). This thermal energy can be stored and delivered to a heat engine to generate electricity whenever it is needed or integrated into other applications, such as supplying industrial process heat. Since inexpensive and large-scale thermal energy storage (TES) can be easily integrated, it allows for industrial-scale dispatchable solar energy production well beyond daylight hours. It is a maturing technology with widespread deployment depending on the technological solution. Abengoa has a leading role in this market, with 34% of the thermosolar power installed capacity worldwide (Figure 1).

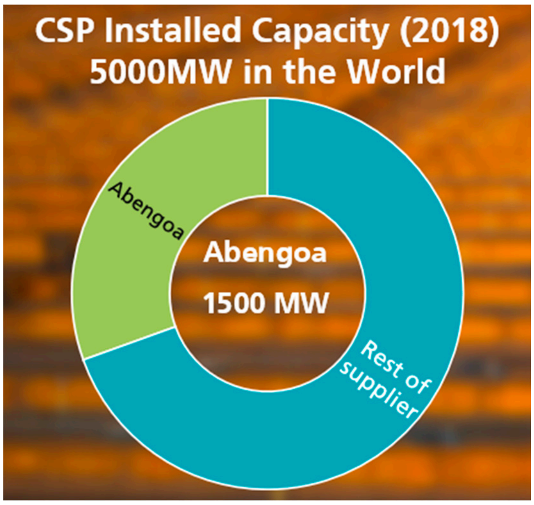

Figure 1. Concentrating solar power (CSP) installed capacity in 2018.

In the past 15 years, CSP has evolved from small scale R&D projects and demonstrators to a mature industry producing electricity at the utility-scale with over 5 GW installed capacity worldwide. The cost of electricity generation with CSP has evolved from 0.35 USD/kWh in 2010 to 0.07 USD/kWh in 2020 [17], see Figure 2. This has only been possible through numerous technological developments. Although many technological targets have been met, this cost reduction has been necessary but insufficient to compete with conventional power generation and the ever-decreasing cost of photovoltaics. CSP has commercially demonstrated the feasibility of large-scale thermal energy storage, providing operational flexibility in high renewable penetrated systems. However, the role that CSP will play in the energy mix is unclear to this date [18].

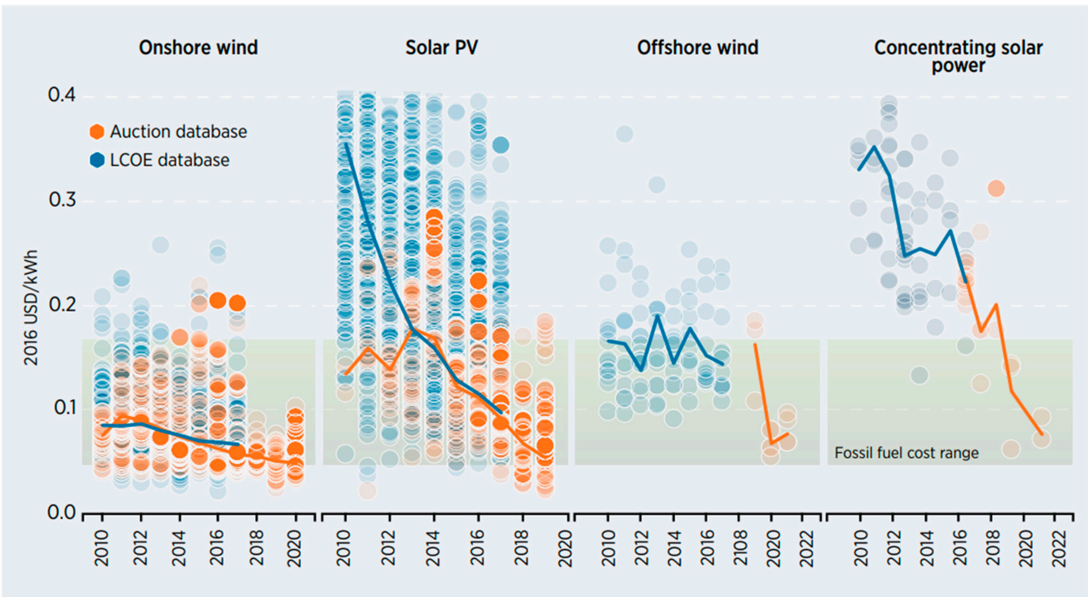

Figure 2. Global levelised cost of electricity and auction price trends for solar photovoltaic (PV), CSP, onshore and offshore wind from project and auction data, 2010–2022 [17].

The CSP business is a global one competing with global markets. But what it is different in this business compared to others is the incessant and frantic technological advance different in the last decades. Companies and staff must maintain constant technological vigilance, keeping up with up to date technology and to be able to bet on it. In this market, technological progress can erode the margins of a product and eliminate a market product, but it can also open up new markets. The current rate of technological replacement in CSP is unprecedented in history.

To compete in such market, strategic planning of technological innovation is needed, involving resources, time, market, business model, competencies, an innovation network, partners, innovation clusters, and knowledge. This successful industrial case of innovation was based on six factors:

1. A case based on the acquisition of new competences in the field of solar energy but that integrated and enhanced the existing competences in conventional power plant engineering.
2. A product innovation to offer renewable solar plants with energy dispatchability. A process innovation for excellence in manufacturing and operation processes.
3. A system innovation (solar plant parabolic through collector and tower plants) but also a component innovation. In a solar plant there are many critical components designed, "ad-hoc" that constitute in themselves new products/equipment for the value chain. Solar receivers, thermal energy storage systems, solar trackers, specific measurement equipment, etc.
4. A disruptive innovation (PS-10 the first commercial solar thermal plant in the world) but also an incremental innovation for cost reduction and efficiency improvement: parabolic trough solar thermal plants with large opening manifolds, tower plants with superheated steam and molten salts.
5. Technological risks: materials in extreme conditions of temperature and pressure, corrosion associated with heat transfer fluids, desert environments and subject to wind loads, physical limits on optical properties, thermodynamic limits.
6. Non-technological component: geographies and first to market.

The strategic planning of innovation in CSP is presented in Table 1. But to achieve success, innovation processes need to be integrated in the company management when driving new products into the market. The stage-gate process enabled Abengoa to determine the moment in which new technologies would become fully profitable by themselves. Stage-gate is a robust standardized and sequential procedure to determine the degree of development of a given project and the amount of investment required to take it to the next step [19,20]. Each process/stage has a corresponding set of requirements and objectives to be accomplished in determining project success or transition to the next stage. The stage-gate procedure is applicable for every product or process development, and its steps are presented in Figure 3.

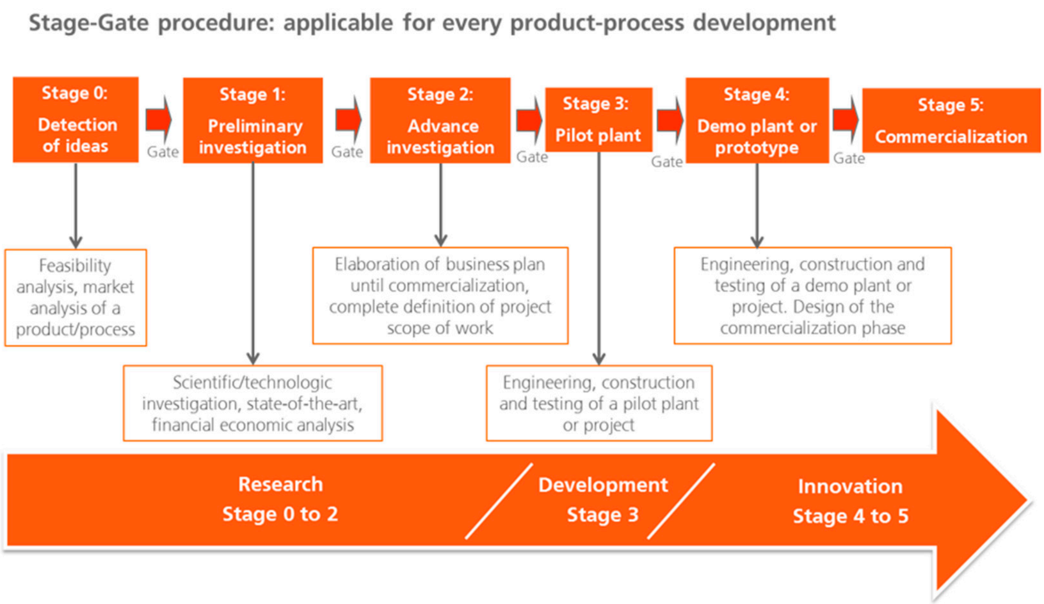

Figure 3. The stage-gate innovation procedure detailed steps.

Table 1. Strategic planning for innovation in CSP at Abengoa.

Strategy	Horizon 1 (2007)	Horizon 2 (2012)	Horizon 3 (2020)
Business and products	Saturated and superheated towers: PS10, PS20, and PS50	- Parabolic trough collector - Molten salt tower and superheater tower	Dispatchability: effective response to the "electricity peak demand"
Objectives: master technologies	- Parabolic trough technology - Superheated steam towers - Saturated steam towers - Heliostats - Molten salts thermal energy storage - Solar field calculation codes	- Molten salt tower - Advanced cycles - Heliostat of the future - Collector of the future	- Design receivers at higher temperature - Seek breakthrough innovations - Hybrid solutions
Main actions	- Support PS10 and PS20 - New funding for research and development (R&D) facilities - Manage IP portfolio - Manage costs and grants follow up	- Operation of molten salt pilot plant - Engineering of a commercial molten salt tower plant - Operation of air receiver solar plant Solugas - Potent maps and IP gap identification	- Assess feasibility of new concepts (high temperature, light management) - New fluids and materials - Technical surveillance - File patents in key technologies

The innovation in Abengoa would not have been possible without the validation of the new technologies at demonstration-scale. The development of new technologies that can be applied to solar power plants be they proprietary or sold to third parties, is one of the competitive advantages on which Abengoa is basing growth and viability of the business in the future. Technological developments in solar energy are occurring very quickly and, for this very reason, the need for viable and efficient alternatives to cope with new projects and market needs.

The Solucar Platform (Figure 4), located in Sanlucar la Mayor, Seville, is a unique facility where solar thermal and photovoltaic technology power plants are operating commercially and which also features pilot plants where technologies can be tested before being brought into commercial use. This platform has become the largest R&D&I centre in the world for solar energy technologies, and Abengoa is the only company that possesses a centre of its kind.

Several facilities were designed, built, and validated and are summarized in Table 2. For the trough technology, the first one was Repow, a 2.1 MW_t trough technology plant (Figure 4). It was used to validate the parabolic trough collectors (PTC) components used in the 50 MW commercial plant Solnova 1, located in Spain. The validation included key components, high optical and tracking accuracy, reduced heat losses, manufacturing simplicity, reduced weight and cost, increased torsional and bending stiffness under wind loads, reduced number of parts and assembly optimization, and corrosion resistance.

The second one is the 9 MWht molten salts dual tank thermal energy storage plant (Figure 4) [21]. The validation included the storage medium (composition, impurities, specifications, etc.) [22], the tanks' design (i.e., heat losses and corrosion) [23,24], the heat exchanger, the molten salts pumps, the freeze protection systems [25], instrumentation and control (I&C), and operation and maintenance (O&M). The project was co-financed by the Center for the Development of Industrial Technology (CDTI).

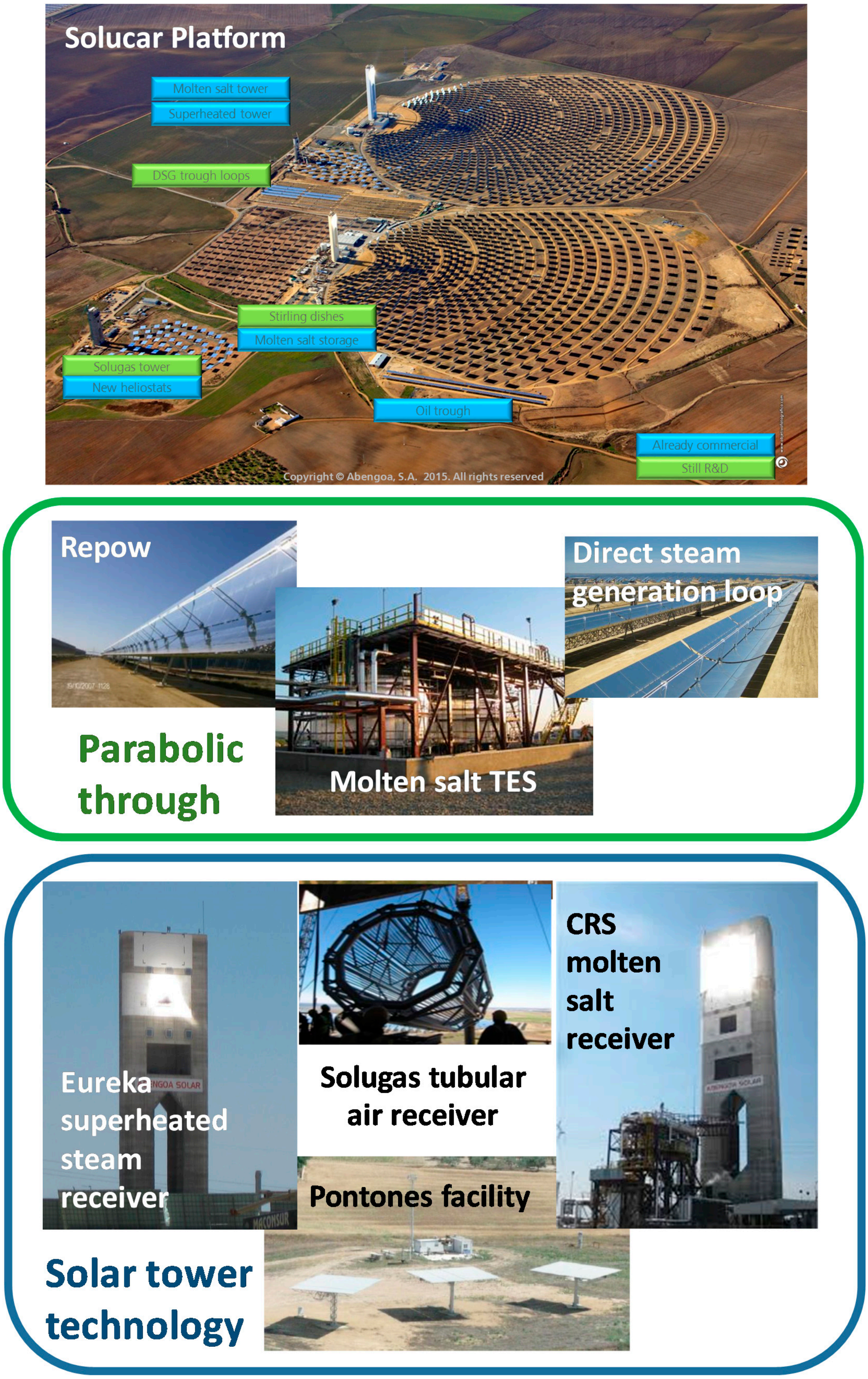

Figure 4. Abengoa Solucar R&D complex with the facilities of technologies validated.

Table 2. Details of the demo facilities used in the roadmap to commercialization.

Type of CSP	Name	Power	Solar Collectors	Heat Transfer Fluid	Maximum Working Temperature	Operation	Hours of Operation	Used in Commercial Plant	Reference
Trough technology	Repow	2.1 MW_t	1 loop of 600 m (4 collector)	Oil	400 °C	2007–2012	30,000 h in 2014	PTC components used in Solnova 1 (Spain) Xina Solar One	[26]
			2 larger aperture collectors of 300 m	Oil	400 °C	2014–2016	500 h	DEWA Hybrid solar-gas plant WAS (Waad Al-Shamal)	[27] [28]
Indirect molten salt storage	Molten salts dual tank TES	9 MWh_t	—	Oil/MS	400 °C	2009–2012	>32,000	Solana Power Plant	[21–24]
Superheater steam receiver	Eureka	5 MW_t	60 heliostats of 120 m^2	Solar salt	550 °C	2009–2011	>2000	Khi Solar One	[29]
Direct steam generation	Eureka-DSG	8 MW_t	3 loops saturated; 2 loops superheated	Water	550 °C	2009–2011	2000	Process heat	[30]
Molten salt receiver	CRS Sales	5 MW_t	85 heliostats of 120 m^2	Solar salt	565 °C	2012–2015	3600	Cerro Dominador	[31]
New HTF	Avanza2	—	—	Ternary carbonate	700 °C	2014–2015	1000	—	[32]
Gas receiver (tubular receiver and volumetric pressurized air receiver)	Solugas	3 MW_t	69 heliostats of 120 m^2	Air	800	2012–2014	1200	—	[33]
	Cersol	105 kWh_t			1000	2014	100	—	—
	Soltrec	3 MW_t			1000	2015	200	—	[34]

Also, two more loops were built, a 3 MWt HTF-loop and an 8 MWt direct steam generation (DSG) loop, co-financed by CDTI, (ITC20111061) (Figure 4) [30]. Abengoa has designed a new large aperture collector and has implemented automotive-style high-rate fabrication and automated assembly techniques to achieve a substantial reduction in the deployment cost.

The second demo facility is the 5 MWth CRS molten salts receiver [31] (Figure 4). The project was co-financed by CDTI (IDI-20090393). Between 2012 and 2015 it validated the receiver, the steam generation, and other main components of the Cerro Dominador commercial plant, located in Chile. This plant AVANZA2 was refurbished in 2015 to test a molten salt loop using different composition salts (a carbonate mixture) working at temperatures above 700 °C to design key components for higher temperature molten salt power plants [32]. The project was co-financed by the CDTI (EXP 00064290 / ITC-20131017).

Another facility is the 3 MWth Solugas site. The Solugas project comprises a pilot tower plant at the Solucar Platform in Seville, Spain, to demonstrate the potential of hybrid solar-gas technology, with direct solar heating of the pressurized air from a gas turbine [33]. The project has been financed by the European Union (EU) 7th Framework Programme. New receiver technologies aimed at increasing the working temperature and allowing new geometries for thermochemical reactions have also been tested at the Solugas site (Figure 4). Cersol is a 105 kWth ceramic tubular receiver working with air at 20 bar and 400–1000 °C. Soltrec is a 1.5 MWth volumetric pressurized air receiver working at 1000 °C [34].

The validation of the optical quality and tracking accuracy of new heliostats is undertaken in Pontones, an installation where the processing of an image focused on a target is done to measure the optical accuracy of the heliostat (Figure 4). The Solnova 1 R&D area allows the optical validation of new collectors (deflectometry and automatic photogrammetric quality system), with an on-site test method for thermal and optical performances of a new parabolic-trough structure (Figure 5).

This would not be possible without building an extensive R&D network. The Abengoa CSP R&D network includes R&D centres (such as CSIC, Tecnalia, CENER, CTM, CIEMAT, IMDEA Energía, and AICIA in Spain; Sandia National Laboratories and NREL in USA; CNRS in France, Fraunhofer and DLR in Germany; CSIRO in Australia; or the Paul Scherer Institut in Switzerland), universities (such as Universitat Politècnica de Catalunya, Universitat de Lleida, Universidad de Zaragoza, Universidad de Huelva, and Universidad Rey Juan Carlos in Spain; Université de Bordeaux in France; School of Mines Colorado in USA; Technische Universität Dresden and Technisch Universität München in Germany; and University of Bath in UK), and other companies (such as AKO, SQM, AalbogCSP, Promat, Fertiberia, BASF, Tok, Qnergy, SQM, SolarTurbines or Sant-Gobain).

The results of such intensive effort in R&D are reflected in the accumulated R&D investment and patents granted (Figure 6). Although the slope in the growth of investment and granted patents is not the same, it is clear that both parameters follow a parallel growth in the presented period of time. Coad and Rao 2008 [3] already stated that R&D and patenting is crucial for fast-growing firms.

Several demonstration facilities were also built to validate the tower technology. The first one is the 3 MW_{th} Eureka superheated steam receiver (Figure 4). It is a superheated steam central receiver located at the top of a 49.8 m high tower working with 35 heliostats of 120 m^2 each. Between 2009 and 2011 it reached 1800 hours of operation and it validated the receiver design of the 50 MW Khi Solar One commercial plant, located in South Africa [29]. The configuration and flow conditions are presented in Table 3.

At the early stages of a technology it is common to find different designs competing with each other, because the ideal/winning solution has not yet been identified among the available technologies. This could explain the investment increase from 2013 to 2014, where Abengoa doubled the investment to continue to mature different technological options in parallel, spanning from parabolic trough cost reductions to development of molten salt towers with TES, to high pressure air receivers for thermochemical reactions to hybrid PV-CSP plants. In addition, Abengoa created in 2013 a specific R&D Lab, Abengoa Research, with more than 400 high-level researchers and the most advanced laboratories to complement the knowledge generated at demo scale with a more fundamental knowledge of basic science (materials studies, fluid dynamic studies, etc.), which also contributed to the investment increase in those years.

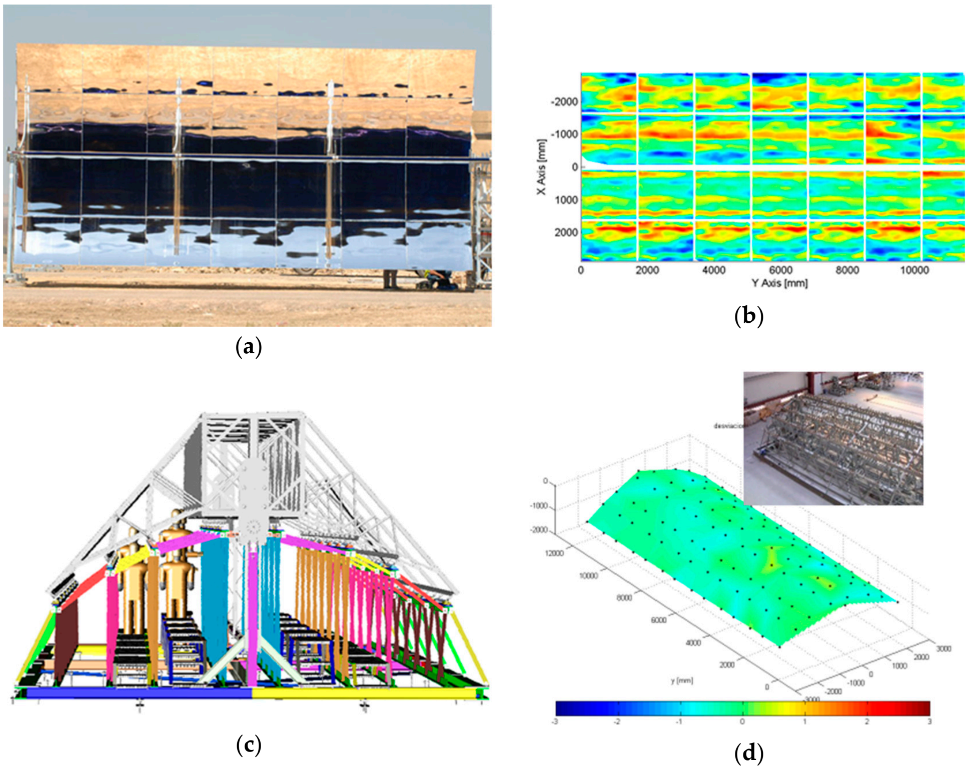

Figure 5. Solnova 1 R&D area for quality control: (**a**) and (**b**) geometric quality parameters by deflectometry and (**c**) and (**d**) jig calibration by photogrammetry.

Table 3. Configuration of the 3 MW_{th} Eureka superheated steam receiver technology for tower power plant.

Receiver Panel Conditions		Flow Conditions	
Paths	2	HTF	Superheated steam
Panels	6	Inlet temperature	300 °C
Passes per panel	4	Outlet temperature	530 °C
Tubes per pass	7	Inlet pressure	85 bar
–	–	Mass flow	3.4 kg/s

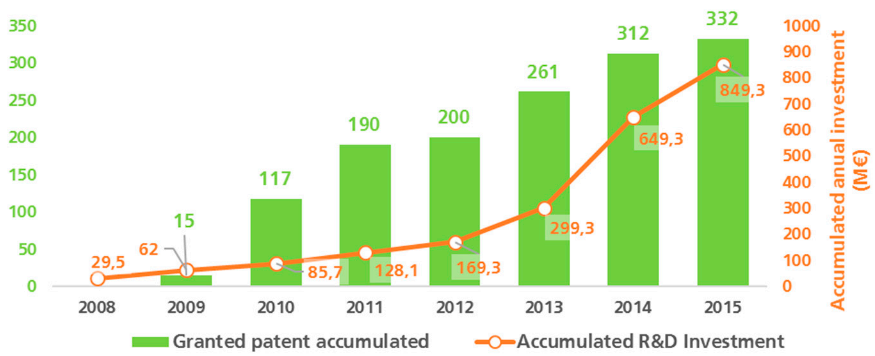

Figure 6. Accumulated R&D investment vs. granted patents in the period 2008–2015.

As expected, the relation between R&D investment and installed commercial CSP capacity follow a more similar slope, growing in a comparable manner (Figure 7). These figures show a similar pattern to that of the Chinese PV technological system (Figure 8): in the early stages a knowledge base for science and technology was first built, as shown by a steep increase in the patents granted (12-fold from 2009–2011, Figure 6), followed by a steady, continuous increase in R&D investment that resulted in a "flowering" phase, where the installed power plant capacity was doubled yearly for several consecutive years (from 2011 to 2012 and from 2012 to 2013, as shown in Figure 7), to a later period where the rate of increase in patents, R&D investment, and plant installed capacity all level off as products reach maturity and the market readjusts itself.

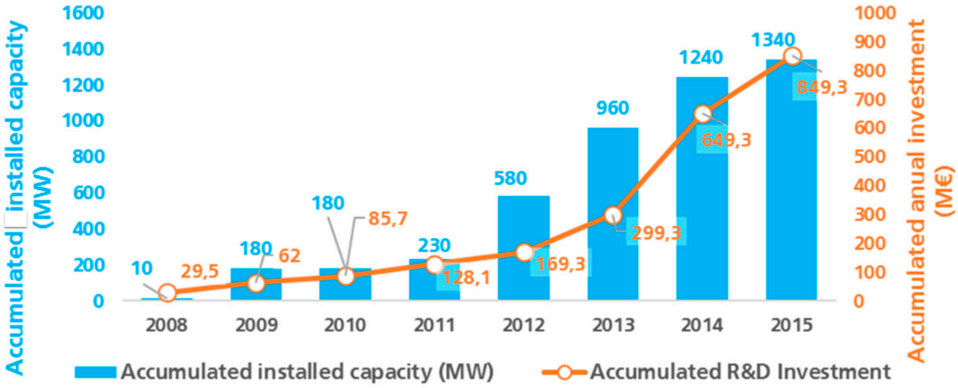

Figure 7. Accumulated R&D investment vs. installed capacity in the period 2008–2015.

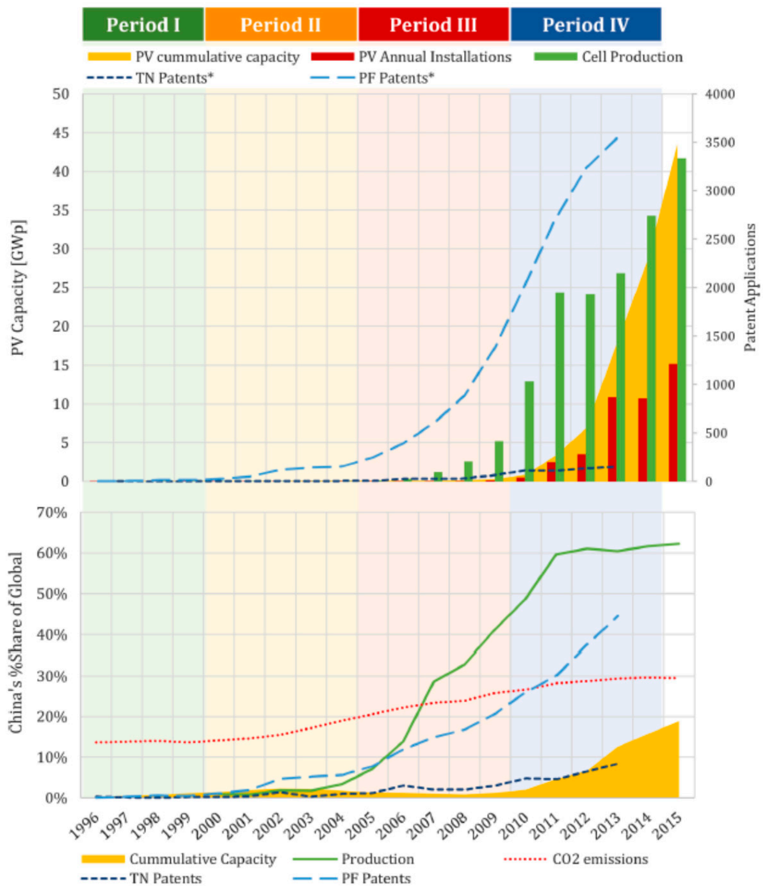

Figure 8. The whole picture of the Chinese PV technological system [5].

3. Case Study: Thermal Energy Storage (TES) for CSP at Abengoa

Let us view in detail the case study of the development of the thermal energy storage (TES) technology for CSP at Abengoa. The most important factor that distinguishes solar thermal energy from other forms of renewable energy generation is manageability or the ability to adapt production to demand. Solar thermal energy is considered to be dispatchable because it enjoys a high thermal inertia that prevents generation from stopping unexpectedly, due, mostly, to molten salt thermal energy storage. TES is very important in commercial CSP because it makes CSP electricity production dispatchable and reliable for grid operators and stable for the plant itself [35]. Moreover, TES has an excellent return efficiency: about 98% when the storage medium is also used as the HTF (direct storage) and about 93% when the storage medium is different from the HTF (indirect storage, Figure 9). But TES increases investment in the commercial plant due to the oversizing of the solar field, the tanks, heat exchangers, molten salts management, other equipment, heat tracing, safety, etc.; increases the O&M costs; and raises technical risks [17].

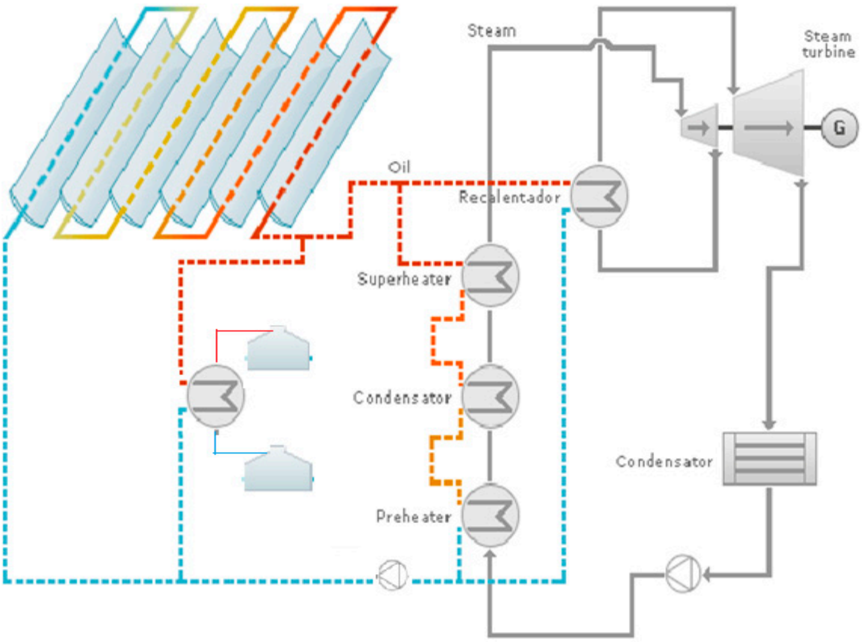

Figure 9. Indirect thermal energy storage (TES) concept for CSP.

Due to the need of this strategic product for the CSP, a roadmap for the development of the TES technology in Abengoa was implemented (Figure 10):

- The first stage was the creation of the R&D network in 2007, funded with the Spanish CENIT project ConSOLida 2008–1005, where the biggest challenges were the confidentiality needed between the company and the R&D institutions, the training activity needed, the need to achieve results following a schedule fixed by market demands, and last but not least, the need to develop deep relationships of trust.

As stated by Cassiman et al., 2018 [36], industry collaborates with universities or research centres to access basic research and to integrate these insights into their own research efforts to generate greater performance outcomes. However, accessing basic research requires complementary actions by the industry, where one of the most important is the translation and integration of the developed knowledge into the innovation process of the company, but this can only be done by individuals. This can only be done through those aforementioned relations of trust. Changes in personnel both at the company or at the research centres usually slow down considerably this knowledge transfer. Moreover, relations of trust are needed both if the relation is based in an institutional mode (interactions are mediated by the university through its administrative structures, such as departments or technology transfer offices) or it is based in personal contractual arrangements with individual researchers [37].

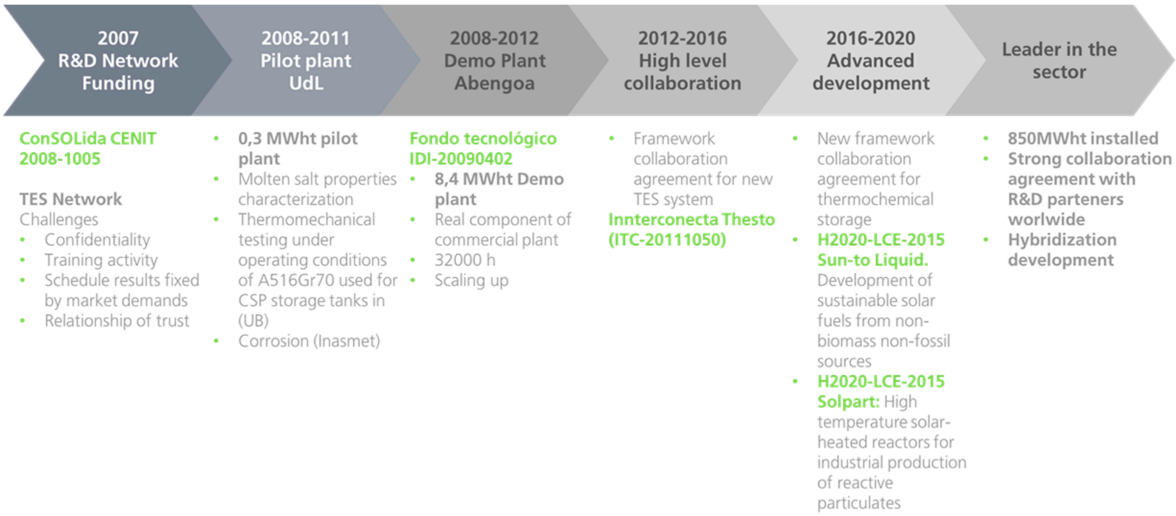

Figure 10. TES development roadmap.

- The second stage was the testing at pilot plant at the University of Lleida, where a 0.3 MWht pilot plant was built to carry out a deep characterisation of the molten salt properties [38]. At the same time research was carried out at the University of Barcelona, where thermomechanical testing under operating conditions of container materials such as A516Gr70 were developed [39], and at Inasmet, where corrosion tests were performed [40].

This step laid into the strategy of addressing success through research collaboration, identifying common denominators between the research institution and the industry [41]. Liew et al. 2013 [42] listed methods that would serve as guideline to best practices, not guaranteeing success, but helping in identifying key factors that could ensure a successful collaboration. Those methods are long-term strategic planning (broken in three components: financial support, transfer of technology, and human capital development and retention) and networking. The development of a pilot plant at a university ensures the long-term strategic planning, and the company and the research institutions doing that together ensures the long-term collaboration.

The third stage was testing at demo plant scale at Abengoa, where an 8.4 MW_{ht} was built to test real components of the future commercial plants and to study the scaling up of the technology. This plant was operated during 32000 hrs. This was funded with the Spanish project Fondo tecnológico IDI-20090402.

- The TES pilot plant was integrated in a parabolic trough plant that uses thermal oil as HTF. The heat transfer fluid cedes heat to the salt through a heat exchanger. The design capacity of the plant was 2.1 MW_{th} with four hours of thermal storage, representing a total thermal capacity of 8.4 MW_{th}. The salts used in this system are the so-called solar salts, comprising a mix of $NaNO_3$ (sodium nitrate) and KNO_3 (potassium nitrate).

The goals of this demo plant were to evaluate the technology on a scale whose results were sufficiently representative of the real problems a commercial plant using this storage technology would face. With this approach, the TES plant came into operation in January 2009 and, since then it has successfully accumulated more than 25,000 h of uninterrupted operation, which has enabled attainment of representative results for the technology analysed. Points such as the corrosion of materials [43], analysis of potential leak points, calculation of performance or actual storage efficiency (including a comprehensive assessment of thermal losses), and an analysis of plant operation, were the main parameters analysed at this plant during its years in operation.

From an operational point of view, the different operating modes of the facility were validated. Their main configurations were in the load mode, discharge mode, standby mode and drainage mode, and in the intermediate steps between each mode. Operation was fully automated and optimized during the test period. Analysis of operation data enabled validation of the efficiency values used in the simulation models which are used as the basis for the design of commercial plants. Similarly, the facility own consumption was evaluated, validating and optimizing design of the thermal insulation and electric heat tracing systems, and the type of instrumentation and valves used in the plant.

Since this pilot plant came into operation, the key components of the technology were also validated. This included an assessment of the vertical pumps and heat exchanger train installed. In addition, ongoing analysis of the salts was carried out to detect whether there is any change in composition during the life of the plant.

- The next step was the development of high-level collaboration with a framework of collaboration agreement of the newly developed TES system (Interconecta Thesto ITC-20111050) to develop a new TES concept for direct steam generation, based on solid particle and phase change materials (PCM) solutions. The idea was to explore alternatives to the molten salt sensible heat TES with more technologically complex solutions, leveraging the baseline developments.

Figure 11 shows the distribution of investment private and public funding on both concepts: the initial molten salt sensible heat TES and further advanced latent heat PCM designs. The molten salt TES required a higher investment because it was the first in-house technology for commercial long-term (+6 h) TES. Additionally, the PCM route has not been fully matured into a commercial product, stalling at stages 2–3 of the stage-gate process, since the financial case has not been as clear (and there was already a working and inexpensive option).

But companies also need to commit to a strategy of accessing basic research and to integrate it to its own innovation process. The literature agrees that partnerships and institutional collaborative agreements are a vehicle to establish such a commitment [1] and that individuals who converse and collaborate generate better ideas than lone inventors [44].

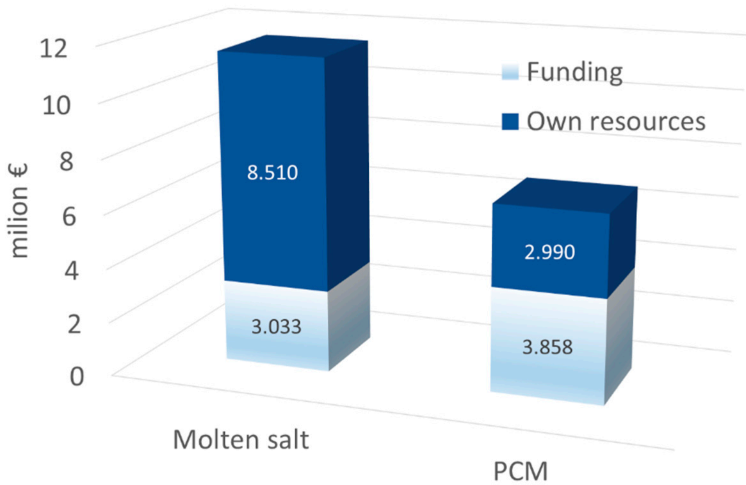

Figure 11. Investment distribution in TES development (2008–2012).

- Then, advanced development of the technology was achieved with several frameworks of collaboration in thermochemical storage with European funding under the H2020 funding scheme.
- To finally achieve leadership in the sector with 6000 MW_{ht} installed in a thermal storage system, strong collaboration agreements with several R&D partners worldwide, and the development of hybridization new concepts.

In this step, the selection of the ideal R&D partners was crucial. As stated by Shaikh and Levina (2019) [45], how organizational decision makers actually pick an alliance partner is not well understood and depends on the company. At this stage of the process, this was more important, since an open innovation approach was sought, where a formal contract or a negotiation on an arrangement was not always possible.

As commented, the indirect molten salt system is a key component in the CSP product. The main step forward to achieve the objectives set up at the beginning of this process was the TES PS 10 demo plant. The roadmap of this plant is shown in Figure 12. The idea for the plant developed in 2007, when Abengoa saw the clear need for and possibility of integrating TES in future commercial CSP plants. The next two steps were a preliminary research (mainly via modelling) and an advanced investigation with preliminary laboratory tests. Step 3 was the testing at pilot plant scale at the University of Lleida with the design of the demo plant with the lessons learnt at the pilot plant. The demo plant led to successful commercialization of the technology, with the commissioning of the solar plant in the USA, which integrates six hours of storage (Figure 13).

This process also had interesting innovation results, and 13 patents and 11 scientific papers were published in Q1 rated journals. Maskus et al. 2019 [46] stated that strong protection of patent rights spur innovation and return of R&D investments in the industry, but in the case study examined, these last results (including publishing scientific papers and participating in conferences) were possible even though there were strong confidentiality agreements were needed at the beginning of the process.

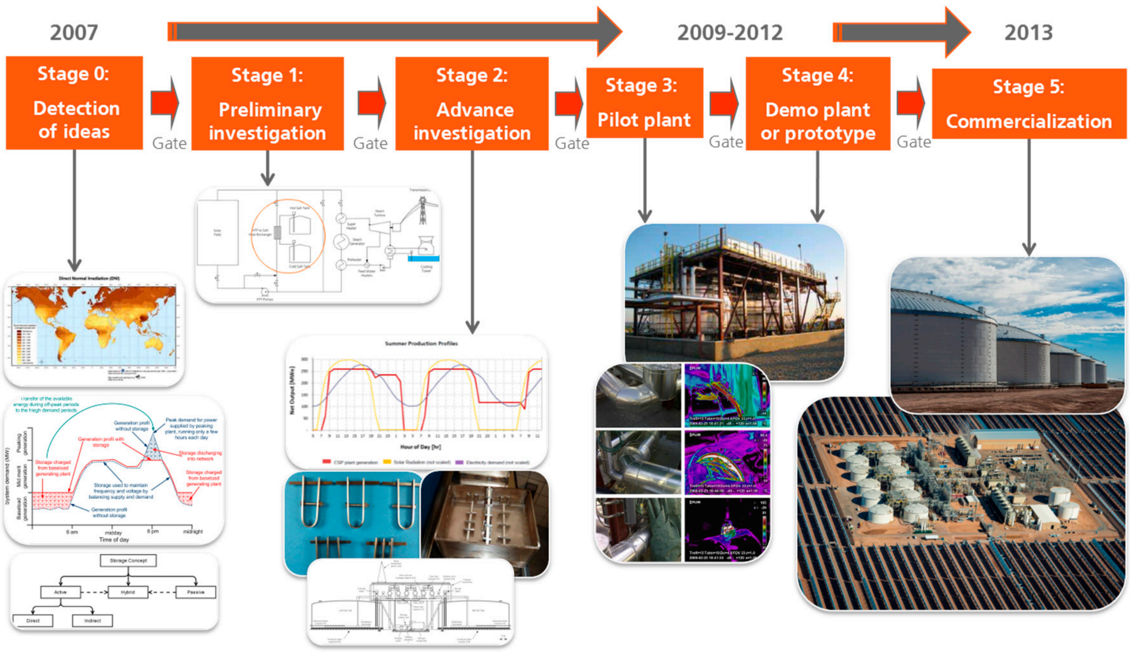

Figure 12. Roadmap to develop TES.

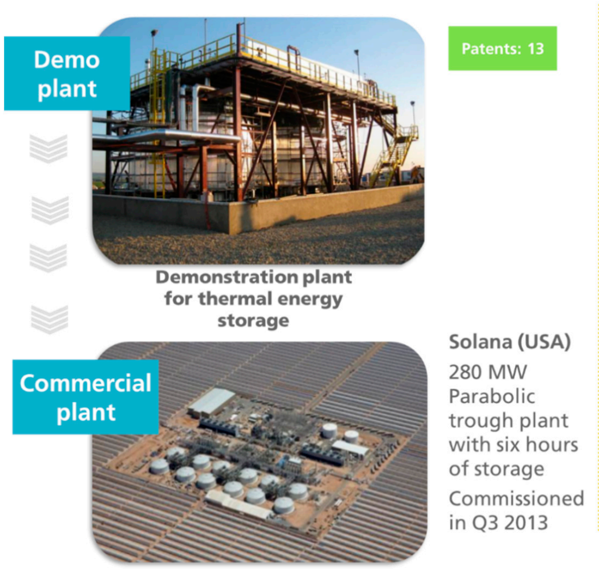

Figure 13. Transition from the demo plant in Seville to the commercial plant in the USA.

4. The Dichotomy: Private versus Public Funding

At present cost reduction of CSP technology is still a key driving force which only seems possible through a continuous R&D investment and product development plan, supported by policy and industry. The "learning rate", as explained by Lilliestam et al. 2017 [47], or cost reduction following the expansion of a technology (investment cost reduction for each doubling of installed capacity) may offer further opportunities if support policies and industrial structure are sustained. However, this has proven to be a challenge.

Policies to support CSP have been variable in time and geographies, showing some discontinuity in their efforts. Several policy regimes regarding CSP have taken place: in 1984–1990 in California (USA), in 2007–2013 in Spain with feed-in tariffs which were subsequently (and retroactively) discontinued, and in 2011–2016 the Department of Energy of the USA established the SunShot Initiative to make CSP cost-competitive by 2020 (Figure 14). After 2013 there has been an expansion to other countries with incentivizing policies in China, South Africa, Morocco and Chile. China 12th Five-Year plan (2011–2015) and 13th Five year plan (2016–2020) have a dedicated plan for solar energy (both CSP and PV) [48]. These policy examples show the lack of continuity, with large intermittency and uncertainty regarding public funding in the sector.

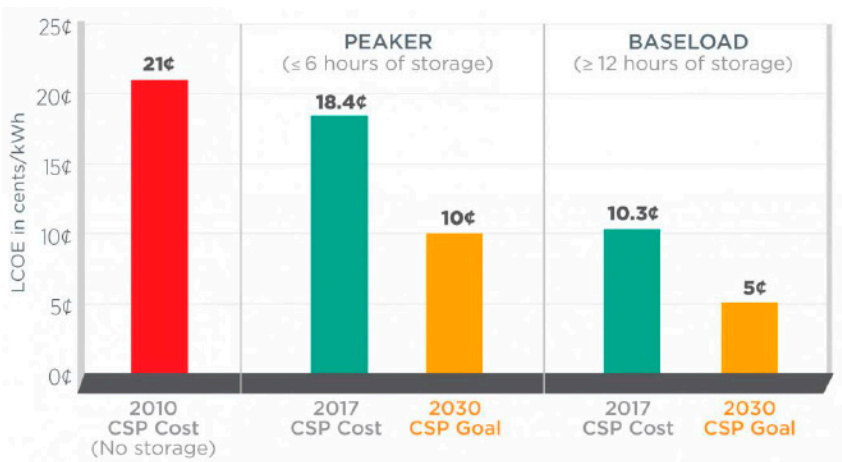

Figure 14. SunShot CSP progress and goals.

At the same time, the cost and financial risk to sustain a pipeline of innovations through continuous R&D are high. Many of the key companies that have driven the current maturity of the CSP technologies (Abengoa, SolarReserve, BrightSource Energy) have been financially impacted by both the constant need to innovate to reduce costs and the large scale of the financial backing for such projects, leading them to reducing or ceasing operations in many cases. At the same time, small and medium enterprises (SMEs) and start-ups do not have the muscle (or financial backing) to undertake complex integrated projects of such kinds and have to focus on small element innovations. Consequently, industry continuity is still a major obstacle for a robust, mainstream and cost-effective deployment.

5. Conclusions

Concentrated solar power has evolved in the past 15 years from small-scale R&D projects to demonstration pilot plants to commercialization. The cost of electricity produced through CSP has decreased from 0.35 USD/kWh in 2010 to 0.07 USD/kWh in 2020. This has been achieved by major players in the market, large and small, through a combination of public and (a large amount of) private funding, embracing innovation from and to the companies through a complex network of R&D collaborations.

In spite of all these achievements, only possible by internalizing the innovation process within the company, CSP is unquestionably still too expensive to compete with other renewable energies.

However, by incorporating (and helping develop) inexpensive long-term thermal energy storage, it offers a path for operational flexibility in highly penetrated renewable decentralized power systems and options for decarbonisation of our society.

In Abengoa, the role of storage is key to guarantee the competitiveness of the CSP, thanks to the dispatchability it offers. Thermal storage gives the necessary stability in the grid with high penetrability of non-dispatchable renewables such as PV or wind. Abengoa made an important commitment to develop this product through a research and innovation strategy, with a short- and long-term strategy implemented during the same period of time. This strategy was fully supported by public funds, although the necessary developments would not have been possible without a strong disbursement from the company. This disbursement is not always feasible for private companies, which limits the technological advances necessary for society. Strong public financing policies are necessary to guarantee the development of new strategic technological products.

Author Contributions: Conceptualization, C.P. and L.F.C.; methodology, C.P. and S.F.; investigation, C.P., S.F. and L.F.C.; resources, C.P. and L.F.C.; data curation, C.P.; writing—original draft preparation, C.P. and S.F.; writing—review and editing, L.F.C.; visualization, C.P.; funding acquisition, C.P. and L.F.C. All authors have read and agreed to the published version of the manuscript.

Funding: The work was partially funded by the by the Ministerio de Ciencia, Innovación y Universidades de España (RTI2018-093849-B-C31- MCIU/AEI/FEDER, UE) and by the Ministerio de Ciencia, Innovación y Universidades - Agencia Estatal de Investigación (AEI) (RED2018-102431-T). Abengoa thanks the Spanish Ministry of Science and Innovation that has allowed us to finance R&D in CSP: CDTI (IDI-20090402, ITC-20111050, ConSOLida CENIT 2008-1005, CDTI IDI-20090393, ITC-20131017); and European Commission: H2020 programme (H2020-LCE-2015 Sun-to Liquid, H2020-LCE-2015 Solpart). We thank the partners of the consortium who have allowed these developments and thank all members of the Abengoa CSP department.

Acknowledgments: Cabeza would like to thank the Catalan Government for the quality accreditation given to her research group GREiA (2017 SGR 1537). GREiA is certified agent TECNIO in the category of technology developers from the Government of Catalonia. This work is partially supported by ICREA under the ICREA Academia programme. We would like to thank the partners of the consortium who have allowed these developments and thank all members of the Abengoa CSP department.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Veugelers, R.; Cassiman, B. R&D cooperation between firms and universities. Some empirical evidence from Belgian manufacturing. *Int. J. Ind. Organ.* **2005**, *23*, 355–379.

2. Cockburn, I.M.; Henderson, R.M. Publicly funded science and the productivity of the pharmaceutical industry. *Innov. Policy Econ.* **2000**, *1*, 1–34. [CrossRef]
3. Coad, A.; Rao, R. Innovation and firm growth in high-tech sectors: A quantile regression approach. *Res. Policy* **2008**, *37*, 633–648. [CrossRef]
4. Lee, H.; Miozzo, M. Which types of knowledge-intensive business services firms collaborate with universities for innovation? *Res. Policy* **2019**, *48*, 1633–1646. [CrossRef]
5. Shubbak, M.H. The technological system of production and innovation: The case of photovoltaic technology in China. *Res. Policy* **2019**, *48*, 993–1015. [CrossRef]
6. Sovacool, B.K.; Jeppesen, J.; Bandsholm, J.; Asmussen, J.; Balachandran, R.; Vestergaard, S.; Andersen, T.H.; Sørensen, T.K.; Bjørn-Thygesen, F. Navigating the "paradox of openness" in energy and transport innovation: Insights from eight corporate clean technology research and development case studies. *Energy Policy* **2017**, *105*, 236–245. [CrossRef]
7. Im, H.J.; Shon, J. The effect of technological imitation on corporate innovation: Evidence from US patent data. *Res. Policy* **2019**, *48*, 103802. [CrossRef]
8. Schoonhoven, C.B.; Eisenhardt, K.M.; Lyman, K. Speeding products to market: Waiting time to first product introduction in new firms. *Adm. Sci. Q.* **1990**, *35*, 177–207. [CrossRef]
9. Ortiz-Villajos, J.M.; Sotoca, S. Innovation and business survival: A long-term approach. *Res. Policy* **2018**, *47*, 1418–1436. [CrossRef]
10. Iqbal, A.M.; Khan, A.S.; Bashir, F.; Senin, A.A. Evaluating national innovation system of Malaysia based on university-industry research collaboration: A system thinking approach. *Asian Soc. Sci.* **2015**, *11*, 45–60.
11. Ivascu, L.; Cirjaliu, B.; Draghici, A. Business model for the university-industry collaboration in open innovation. *Procedia Econ. Financ.* **2016**, *39*, 674–678. [CrossRef]
12. Chesbrough, H. Open Innovation Results: Going Beyond the Hype and Getting Down to Business. 2019. Available online: https://www.oxfordscholarship.com/view/10.1093/oso/9780198841906.001.0001/oso-9780198841906 (accessed on 7 June 2020). [CrossRef]
13. Xu, K.; Huang, K.F.; Gao, S. Technology sourcing, appropriability regimes, and new product development. *J. Eng. Technol. Manag.* **2012**, *29*, 265–280. [CrossRef]
14. De Silva, M.; Howells, J.; Meyer, M. Innovation intermediaries and collaboration: Knowledge–based practices and internal value creation. *Res. Policy* **2018**, *47*, 70–87. [CrossRef]
15. Bowonder, B.; Miyake, T. Technology management: A knowledge ecology perspective. *Int. J. Technol. Manag.* **2000**, *19*, 7–8. [CrossRef]
16. Grillitsch, M.; Schubert, T.; Srholec, M. Knowledge base combinations and firm growth. *Res. Policy* **2019**, *48*, 234–247. [CrossRef]
17. IRENA. Renewable Power Generation Costs in 2017. 2018. Available online: https://www.irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017 (accessed on 7 June 2020).
18. Siegel, N. Where do we go from here? *ASME J. Sol. Energy Eng.* **2019**, *141*, 020301. [CrossRef]
19. Cooper, R.G. Stage-gate systems: A new tool for managing new products. *Bus. Horiz.* **1990**, *33*, 44–54. [CrossRef]
20. Cooper, R.G. The drivers of success in new-product development. *Ind. Mark. Manag.* **2019**, *76*, 36–47. [CrossRef]
21. Cabeza, L.F.; Prieto, C.; Miró, L.; Gasia, J.; Peiró, G. Design and start-up of two pilot plants for molten salts storage testing. In *Energy Sustainability*; 2016; 9p, ES2016-59268, V001T04A009; Available online: https://asmedigitalcollection.asme.org/ES/proceedings-abstract/ES2016/50220/V001T04A009/231285 (accessed on 7 June 2020).
22. Prieto, C.; Ruiz-Cabañas, F.J.; Rodríguez-Sanchez, A.; Rubio Abujas, C.; Fernández, A.I.; Martínez, M.; Oró, E.; Cabeza, L.F. Effect of the impurity magnesium nitrate in the thermal decomposition of the solar salt. *Sol. Energy* **2019**, *192*, 186–192. [CrossRef]
23. Prieto, C.; Osuna, R.; Fernández, A.I.; Cabeza, L.F. Molten salt facilities, lessons learnt at pilot plant scale to guarantee commercial plants; heat losses evaluation and correction. *Renew. Energy* **2016**, *94*, 175–185. [CrossRef]
24. Prieto, C.; Osuna, R.; Fernández, A.I.; Cabeza, L.F. Thermal storage in a MW scale. Molten salt solar thermal pilot facility: Plant description and commissioning experiences. *Renew. Energy* **2016**, *99*, 852–866. [CrossRef]

25. Prieto, C.; Rodríguez-Sánchez, A.; Ruiz-Cabañas, F.J.; Cabeza, L.F. Feasibility study of freeze recovery options in parabolic trough collector plants working with molten salt as heat transfer fluid. *Energies* **2019**, *12*, 2340. [CrossRef]
26. Abengoa. 2017. Available online: http://www.abengoa.es/web/es/noticias_y_publicaciones/noticias/historico/2017/08_agosto/20170816-NP-Xina.html (accessed on 20 May 2020).
27. Mohammed bin Rashid Al Maktoum Solar Park. 2020. Available online: https://www.dewa.gov.ae/en/about-us/strategic-initiatives/mbr-solar-park (accessed on 20 May 2020).
28. CSP Focus. Waad al Shamal. 2017. Available online: http://www.cspfocus.cn/en/market/detail_262.html (accessed on 20 May 2020).
29. Abengoa. 2016. Available online: http://www.abengoa.com/web/en/noticias_y_publicaciones/noticias/historico/2016/02_febrero/abg_20160205.html (accessed on 11 March 2020).
30. Alguacil, M.; Prieto, C.; Rodriguez, A.; Lohr, J. Direct steam generation in parabolic trough collectors. *Energy Procedia* **2014**, *49*, 21–29. [CrossRef]
31. Montero, C.; Navío, R.; Llorente, P.; Romero, M.C.; Martínez, J. CRS sales: Abengoa's molten salt pilot power tower plant celebrates one year of uninterrupted operation. *Energy Procedia* **2014**, *49*, 488–497. [CrossRef]
32. Prieto, C.; Fereres, S.; Ruiz-Cabañas, F.J.; Rodriguez-Sanchez, A.; Montero, C. Carbonate molten salt solar thermal pilot facility: Plant design, commissioning and operation up to 700 °C. *Renew. Energy* **2020**, *151*, 528–541. [CrossRef]
33. Quero, M.; Korzynietz, R.; Ebert, M.; Jiménez, A.A.; del Río, A.; Brioso, J.A. Solugas—Operation experience of the first solar hybrid gas turbine system at MW scale. *Energy Procedia* **2014**, *49*, 1820–1830. [CrossRef]
34. Del Rio, A.; Korzynietz, R.; Brioso, J.A.; Gallas, M.; Ordóñez, I.; Quero, M.; Díaz, C. Soltrec—Pressurized volumetric solar air receiver technology. *Energy Procedia* **2015**, *69*, 360–368. [CrossRef]
35. González-Roubaud, E.; Pérez-Osorio, D.; Prieto, C. Review of commercial thermal energy storage in concentrated solar power plants: Steam vs. molten salts. *Renew. Sustain. Energy Rev.* **2017**, *80*, 133–148. [CrossRef]
36. Cassiman, B.; Veugelers, R.; Arts, S. Mind the gap: Capturing value from basic research through combining mobile investors and partnerships. *Res. Policy* **2018**, *47*, 1811–1824. [CrossRef]
37. Bodas Freitas, I.M.; Geuna, A.; Rossi, F. Finding the right partners: Institutional and personal modes of governance of university–industry interactions. *Res. Policy* **2013**, *42*, 50–62. [CrossRef]
38. Peiró, G.; Prieto, C.; Gasia, J.; Jové, J.; Miró, L.; Cabeza, L.F. Two-tank molten salts thermal energy storage system for solar power plants at pilot plant scale: Lessons learnt and recommendations for its design, start-up and operation. *Renew. Energy* **2018**, *121*, 236–248. [CrossRef]
39. Prieto, C.; Gallardo-González, J.; Ruiz-Cabañas, F.J.; Barreneche, C.; Martínez, M.; Segarra, M.; Fernández, A.I. Study of corrosion by Dynamic Gravimetric Analysis (DGA) methodology. Influence of chloride content in solar salt. *Sol. Energy Mater. Sol. Cells* **2016**, *157*, 526–532. [CrossRef]
40. Ruiz-Cabañas, F.J.; Prieto, C.; Osuna, R.; Madina, V.; Fernández, A.I.; Cabeza, L.F. Corrosion testing device for in-situ corrosion characterization in operational molten salts storage tanks: A516 Gr70 carbon steel performance under molten salts exposure. *Sol. Energy Mater. Sol. Cells* **2016**, *157*, 383–392. [CrossRef]
41. Rajalo, S.; Vadi, M. University-industry innovation collaboration: Reconceptualization. *Technovation* **2017**, *62–63*, 42–54. [CrossRef]
42. Liew, M.S.; Tengku Shahdan, T.N.; Lim, E.S. Enablers in enhancing the relevancy of university-industry collaboration. *Procedia Soc. Behav. Sci.* **2013**, *93*, 1889–1896. [CrossRef]
43. Ruiz-Cabañas, F.J.; Prieto, C.; Madina, V.; Fernández, A.I.; Cabeza, L.F. TES-PS10 postmortem tests: Carbon steel corrosion performance exposed to molten salts under relevant operation conditions and lessons learnt for commercial scale-up. *J. Energy Storage* **2019**, *26*, 100922. [CrossRef]
44. Hasan, S.; Koning, R. Conversations and idea generation: Evidence from a field experiment. *Res. Policy* **2019**, *48*, 103811. [CrossRef]
45. Shaikh, M.; Levina, N. Selecting an open innovation community as an alliance partner: Looking for healthy communities and ecosystems. *Res. Policy* **2019**, *48*, 103766. [CrossRef]
46. Maskus, K.E.; Milani, S.; Neumann, R. The impact of patent protection and financial development on industrial R&D. *Res. Policy* **2019**, *48*, 355–370.

47. Lilliestam, J.; Labordena, M.; Patt, A.; Pfenninger, S. Empirically observed learning rates for concentrating solar power and their responses to regime change. *Nat. Energy* **2017**, *2*, 17094. [CrossRef]
48. Arrilucea, E.; Kuittinen, H. Case Study Report: US SunShot Initiative and Reflections of the Chinese Solar Energy Policies. 2018. Available online: http://www.jiip.eu/mop/wp/wp-content/uploads/2018/09/US_SunShot_ArriluceaKuittinen.pdf (accessed on 7 June 2020).