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Rethinking the dynamics of innovation, science, and technology: The curious case of Stirling engines and Stirling refrigerators

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A R T I C L E I N F O

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A B S T R A C T

"Technological innovation" has become a catch phrase of contemporary policy making for governments, corporations and academic organizations. For many it has become an article of faith that technological innovation is the key to solving energy transition and environmental problems, but the formula for success is not obvious. The phrase "science and technology" rolls off the tongues of energy related policymakers, managers and researchers spontaneously, as if this is the natural order of things, but why is the converse phrase "technology and science" so rarely encountered? The popular view appears to be that energy technology is applied energy science, or that technological change in the field of energy technologies flows naturally from scientific progress. However, what if popular preconceptions about the relationship between science and technology in the energy field are misplaced? This paper addresses the question of the fundamental relationship between technology and science by first analyzing historical cases of two representative energy-conversion technologies, then reviewing pertinent literature from the field of science, technology and society (STS) studies, and finally investigating empirically the nature of the relationship using statistical data analysis. It draws policy-making implications for investment in energy technology and science. We propose the *hypothesis of technology-conditioned science* as a plausible and credible counterweight to extant commonplace presumptions that science is the precursor of low-carbon energy-conversion technologies.

1. Introduction

"What's better, a scientist or an engineer? Who wins?" This question was put to Elon Musk, the energy technology entrepreneur and co-founder and CEO of Tesla Motors, during an interview at a science and engineering festival in 2012. He replied [1]:

> So, everyone is sitting around and waiting for a bloody [Large Hadron] Collider… If physics was really driving things, why aren't there advances being made? … it is clearly the engineering of the Collider that drives the advancements.

Musk's response evokes the question of which domain of human activity—science or technology—should be prioritized by the public when addressing great societal challenges such as the energy transition and climate change. In her address to the Royal Society in London, on receipt of an award for her extraordinary contributions to the promotion of science and science in society, Chancellor Angela Merkel of Germany suggested that the answer to this question is clear, namely, science [2]:

> …during my term as Federal Chancellor, the Federal Government has repeatedly declared that the prosperity of a country such as Germany, with its scarce mineral resources, must be sought through investment in research, education and science, and this to a disproportionate degree.

Chancellor Merkel's perspective was recently echoed by President Rumen Radev of Bulgaria in a 2021 speech he delivered as part of his country's role in hosting the *Three Seas Initiative* (3SI) of twelve European countries, in which he also stressed the key role of science [3]:

> Cooperation in the field of innovation and scientific research is of key importance for achieving the Three Seas Initiative (3SI) connectivity goals in the field of energy, transport and digitalization.

On the other side of the Atlantic, in a February 2021 speech, the newly appointed Secretary of the United States Department of Energy, Jennifer M. Granholm, concurred with her European counterparts in emphasizing the primacy of science [4]:

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> Here at the Department of Energy, we have the world's most brilliant scientists and energy experts figuring out all the ways to make [clean, abundant, cheap power made right here in the U.S.] happen.

The presumption in the field of energy that science is the original source of innovation and that energy science typically precedes energy technology is also embraced, consciously or otherwise, by a variety of contemporary energy researchers, as illustrated by the following examples:

> … innovation [is] a more critical component of cost reductions compared to deployment. For instance, if scientists increase battery energy densities by 20% through extensive R&D in materials science, yet continue to use materials and production lines at their current cost, the price per kWh of storage could drop by 16.7% before increasing any production volumes. [5]

> A second role [of the government] is stimulation of technology development and support for the underlying science that enables development. [6]

As the vicissitudes of climate change and environmental stress create pressure for our societies to transition towards a low-carbon economy, understanding the process of how advanced energy technologies actually develop is important for national and international policymakers [7]. Enriching our understanding of this process is also the underlying purpose of this paper.

The topic of the relationship between science, technology and society ("STS") has received much attention in the scholarly literature [8–10]. In particular, the simplistic view that science is *the* source of technological innovation and societal progress has for decades been criticized by academics in the field of STS studies [11–13]. Although some governments have recently changed the rhetoric of their narrative from "science policy" to "innovation policy" [14], the above quotes (with the exception of the comment by Musk), nevertheless suggest that amongst policymakers and practitioners in the energy field, as well as amongst university laboratory scientists (as opposed to scholars in the field of STS studies), the presumption of science being the primary solution to societal challenges remains ubiquitous. In short, it appears that the critical debates about science and society that have emerged within the halls of academia during the last several decades have, for the most part, taken place beyond the earshot of practicing scientists and policymakers. In the domain of energy technology there appears to be a disjuncture between the dominant perspective of STS scholars and the presumptions that dominate in the thinking of laboratory scientists and those outside academia. Which point of view is correct?

Would a careful review of representative historical examples confirm or undermine the popular presumption outside the domain of academic STS studies that scientists rather than engineers are the first movers in developing low-carbon energy-conversion technologies? What implications may be educed from the annals of STS literature for an innovation model for low-carbon energy technologies? What patterns of knowledge creation would we discover if we analyzed thousands of scientific publications and patents related to representative energy-conversion systems? In this paper we aim to find answers to these questions.

A recent survey of the STS and energy social science literatures indicates that opportunities remain for the utilization of STS concepts, applications, and interpretations in energy social science, and for their further refinement and development based on insights from energy technology research [15]. The research reported in this paper adopts the sociotechnical approach to energy research in the wake of recent research on the emergence and diffusion of low-carbon energy technologies that has employed the sociotechnical transitions perspective [16], and the recent publication of incisive analysis of sociotechnical agendas in energy and climate research [17]. Accordingly, to obtain new insights about the emergence and diffusion of low-carbon energy-conversion technologies, and to build bridges for a successful energy transition, we employ a multiple methods research design incorporating two case studies, a systematic STS literature survey, and statistical analyses of bibliographic and patent data from one particular field of energy technology [18].

The primary research question addressed in this paper is: *what sociotechnical activities—scientific research or technology development—tend to arise first in the emergence of low-carbon energy-conversion technologies?* To answer this question, we adopted four research objectives:

1. Identify representative cases of low-carbon energy-conversion systems for prime movers (engines) and heat pumps (refrigerators);
2. Conduct a historiographic case study of two representative cases to construct a pre-search hypothesis of the knowledge emergence process;
3. Conduct a systematic review of the STS literature to test and revise the pre-search hypothesis into a formal research hypothesis;
4. Conduct a statistical analysis of bibliometric data for technological and scientific literature to test the research hypothesis.

The authors approached the first three objectives by analyzing secondary sources from the literature. Section Two discusses the selection of the representative technologies for prime movers and heat pumps, which are the Stirling engine and the Stirling refrigerator respectively. Section Three presents a historiographical case analysis of selected technologies and offers a pre-search hypothesis. Section Four provides a systematic literature review of the STS literature, and tests and revises the pre-search hypothesis into a research hypothesis with testable predictions. Section Five provides a detailed discussion of the methodology employed to analyze bibliometric and patent data related to the fourth objective. Sections Six, Seven and Eight, respectively, present, discuss and draw conclusions about the results of this study.

Our findings may help policymakers, investment experts and philanthropists to prioritize support for technological and scientific activities when developing low-carbon energy-conversion systems. In addition, this paper may be useful to energy practitioners and researchers when constructing research and development plans for novel energy converters.

2. Selection of representative cases of low-carbon energy-conversion technology: The Stirling thermodynamic cycle

We selected Stirling energy-conversion technology—or simply "Stirling technology"—as a representative example of such low-carbon systems. Stirling technology—along with other well-known technologies such as the wind turbine, the solar panel, the fuel cell, the thermoelectric generator, and the vapor-compression refrigerator (that is installed in most, if not all, kitchen refrigeration cabinets)—is a type of energy-conversion technology. Stirling technology, which consists of technical artifacts or systems in which the Stirling thermodynamic cycle is employed in the form of either engines or refrigeration systems, may arguably form an integral part of the global transition to a low-carbon energy future [19–24].

Named after its inventor, Robert Stirling (1790 to 1878), it involves the conversion of energy using the "Stirling" thermodynamic cycle. A distinctive characteristic of this technology is that it can either convert thermal energy into useful mechanical work, playing the role of the *Stirling engine* [25], or convert mechanical work into cooling capacity, playing the role of the *Stirling refrigerator* [26]. We use the term *"Stirling technology"* here to cover both the *Stirling engine* and the *Stirling refrigerator*.

The dual operation of Stirling technology, as either an engine or a refrigerator, is due to a unique combination of thermodynamic processes in the Stirling cycle. This cycle, based on the fundamental principles of thermodynamics, comprises a sequence of four physical processes whereby the working fluid within the machine produces the desired effect, either work or cooling. These four consecutive processes include compression with constant temperature, heating with constant volume, expansion with constant temperature, and cooling with constant volume. The processes thus entail a *controlled* change of gas temperature, pressure, and volume. Depending on the sequence of these processes—forward or reverse—this thermodynamic approach represents the operation of the heat engine or refrigerator.

On a technical level, Stirling technology has several common features with other low-carbon systems, such as the wind turbine, the solar panel, the fuel cell, the thermoelectric generator, and advanced vapor-compression heat pumps. The material nature of the hardware devices required for controlling energy-conversion processes in these branches of energy technology is similar to that of Stirling technology. The laws of energy conversion and heat transfer are universal. The knowledge embedded in low-carbon energy-conversion systems—related to fields such as heat transfer, gas and fluid dynamics, strength and fatigue, vibrations, electromagnetism and electronics, etc.—is similar, no matter the particular branch of energy technology under consideration. Hence we selected the Stirling engine as a representative case for prime movers and the Stirling refrigerator as a representative case for heat pumps.

Another intriguing feature of Stirling technology, however, is that despite the fact that it was invented over two centuries ago—and notwithstanding the fact that since then it has been the subject of thousands of scientific publications, patents, government reports and conference discussions, as well as many corporate and government projects for a variety of practical applications, supported by a great deal of research and development—its adoption to date in commerce has been modest [19,20,27–30]. It appears that the limited impact of Stirling technology in practice may not be explained by technical factors alone, if at all, but rather by contextual factors related to the economy, society and policy [19,27,30]. From the sociotechnical point of view, Stirling technology is therefore similar to other alternative low-carbon energy converters that are promising new candidates for integration in to energy infrastructures, but which have not yet gained wide acceptance.

The recent emergence of the *sociotechnical systems* approach to analyzing energy transitions and the development of energy technologies as part of those transitions [15–17,31–33] presents a potentially fruitful perspective from which to consider the history and future prospects of Stirling technology, and to suggest pathways forward for realizing its practical potential. The sociotechnical systems approach to energy research has emerged within the interdisciplinary academic field of "Science, Technology and Society" or "Science and Technology Studies" (STS), mentioned briefly in Section One, that has been defined as "the study of the processes by which scientific knowledge and technological artifacts are constructed (developed, maintained, and changed) and also the study of the changes in the broader social and material worlds that occur as part of the mutual shaping, co-constitution, or coproduction of science and technology with society and the natural environment" ([15], p. 1).

The history of Stirling technology, that now extends over two hundred years, has generated considerable raw material for systematically investigating the dynamic relationships between the three domains of science, technology and society, and for illuminating some of the issues addressed in the sociotechnical systems literature. The peculiar origins of Stirling technology—while of course embedded in a distinctive social context—raise some especially interesting questions about one axis in the triad, namely, the technology-science axis. In this paper we therefore focus our attention on the relative roles of technology and science within the larger sociotechnical systems context surrounding Stirling technology. However, the results are arguably representative of other energy-conversion systems.

3. Historical case studies of Stirling technology

Since its inception in 1816, Stirling technology has attracted academic, military and commercial interest due to its promise of producing useful work (or cooling capacity) using any source of heat as input energy (for engines), while also exhibiting high reliability and efficiency (especially at non-nominal loads), low noise level, and eco-friendliness. At the beginning of the 19th Century, the industrial zeal for coal led to the excavation of deep mines flooded by underground waters. Steam engine pumps dried the mines, but they frequently exploded due to the weak iron-based construction materials of boilers. The high-pressure steam would often burst violently, inflicting casualties amongst the mine workers. At that time, Robert Stirling, a clergyman of twenty-six years of age, designed a pumping engine that would employ a principle of heat recycling (regeneration) and be safer by operating air as a working gas instead of vapor [34].

In 1818 a 1.5 kW "Stirling" engine was built to pump water in the Ayrshire mines of Scotland. Its low power was the main disadvantage. Robert and his brother, the engineer James Stirling, then together designed and patented in 1827 a more powerful engine that would operate compressed air [35, cf. 36]. It is unclear how many prototypes they built before succeeding with implementing the novel design, but 13 years later, in 1840, the Stirling brothers patented a modified engine [37,38], two versions of which were built in 1842 (15 kW) and in 1843 (33 kW). The latter engine was operating for several years in the Dundee factory for casting metals until it developed cracks in the four-tone heaters due to insufficient strength of the material. In 1845, Robert Stirling gave a lecture about the operation of the 1843 engine at a conference of the Institution of Civil Engineers [39]. The first publication of results related to the Stirling engine can be attributed to 1861 when *Scientific American* published an article discussing the operational results of the 1842 engine [40]. Interestingly, the article misleadingly attributed the creation of the engine to Robert's brother, James Stirling. After the invention of Bessemer steel in 1856, the material strength and power of steam engines grew, which led to their outperforming and obliterating the Stirling engine in practice for almost 100 years.

The concept of a refrigeration machine that employs a similar heat recycling principle to that of the Stirling engine is commonly attributed to the British polymath John Herschel who wrote to *The Athenaeum* on December 24, 1849 [41]:

> … within the last four or five years I have explained orally to my friends a process … as practically applicable to the manufacture of ice for sale on great scale …

> Herschel supported his claim by citing a letter from his friend:

> Dear [John] … I have a clear recollection … of thy suggesting that advantage might be taken of the reabsorption of heat [heat recycling] … This conversation took place either at the anniversary dinner of the Royal Astronomical Society in the early part of 1848,—or at the Greenwich visitation a few weeks afterwards.

Developments of the technology in this direction were continued by the Scottish engineer, Alexander Kirk. He obtained three patents, one in 1862 and two in 1869, for different configurations of refrigeration machines that he called "dry-air machines." Kirk manufactured them for cooling shale oil and large quantities of water in breweries [42]. In 1874, Kirk published a paper where he described the design, principle of operation and considerable experimentation effort related to his inventions [43]. Kirk did not call his machines "Stirling refrigerators," but the term was later widely adopted due to the similarity of the thermodynamic processes in both engines and refrigerators. In this paper we employ the latter term, Stirling refrigerators, in accordance with common practice.

It is difficult to trace a consistent record of scientific and engineering work on Stirling technology earlier than 1960. From the 1930s to the 1960s, limited instances of the technology development in the field emerged in laboratories of large industrial companies such as Philips and General Motors for engines [25], and Philips for refrigerators [44]. Detailed information about this work was generally unavailable and was made accessible to the public only in the form of sometimes opaque patent publications. The prospects of industrial development and later governmental funding of Stirling technology nevertheless helped the general scientific and engineering community to catch a glimpse of light in this field. It was only in the 1960s that a noticeable number of pertinent patents and scientific publications began to emerge.

Several interesting observations may be made about the inception of Stirling engines and refrigerators. The inventors in both instances were not scientists. They were engineers or, in the case of Robert Stirling, a layperson working with the help of engineers. Robert Stirling was a clergyman, without either scientific or engineering credentials. His brother, James Stirling, was an engineer and played a critical role in the development of the technology. John Herschel's work may not be justifiably described as the "scientific" development of regenerative refrigerators. We have been unable to locate any formal publications of his work … and his reference to an informal discussion with a friend at a dinner party should not be considered "science" as such! The creation of regenerative refrigerators was the result of systematic work by the experimental engineer, Alexander Kirk. Another observation is that the first identifiable publications related to the Stirling technology were patents and not scientific papers. The physical machines were applied in practice subsequent to patent publications and were frequently modified, on a learning-by-doing basis, with new patents and the building of new machines. Knowledge about the design and operation of the technology accumulated over many years (29 years for the engine and 12 years for refrigerators) before scientific presentations and publications summarized the results and reflected on limitations and future work. As illustrated in Fig. 1, the development of both engines and refrigerators followed this sequence.

The sequence in Fig. 1 reflects the fact that scientific activity consisted mostly of reflections and theorizing on results obtained during engineering experimentation. The primary source of knowledge during the engineering phase was practical exploratory experimentation, a trial-and-error mode of activity, or learning by doing. Only later was the aggregation of this experience presented and analyzed in conference proceedings and publications. Since these observations demonstrate how the development process of Stirling technology (and possibly of other energy-conversion technologies) works, we hypothesize that a similar sequence would be realized after the 1960s when the development of Stirling technology would gain international momentum with systematic work and the public reporting of results.

4. The relationship between technology and science

Following our introductory review of the historical emergence of Stirling technology, in the context of the recent emergence of the sociotechnical systems approach to energy studies, we will now review what the STS literature has to say about the enigma of the fundamental relationship between science, technology and society. As illustrated in Fig. 2, a ubiquitous question in the STS literature concerns what is the strength and direction of the causal relationships, if any, between the three focal domains.

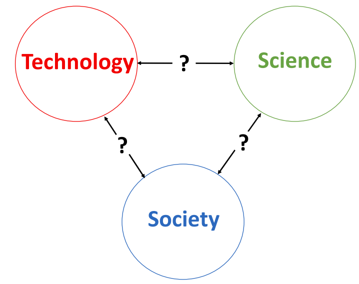

Fig. 2. The Enigma of Science, Technology and Society.

Rather than seek to unravel the whole enigma, in this paper we direct our attention primarily to just one of the three axes of interest, namely the interaction between technology and science. While we focus on the technology-science relationship, we nevertheless take in to account insights from the literature about both the technology-society relationship and the science-society relationship insofar as they have a bearing on the technology-science relationship.

The core theoretical question in our study is: *which comes first, technology or science?* In asking this question we have two things in mind. Firstly, in a historical sense, within a particular field of technological practice—e.g., agriculture, power generation, power transmission, construction, aeronautics, pharmaceuticals, telecommunications, automotive systems, manufacturing, weapons, or medical informatics, etc.—was the emergence of new technology preceded by scientific discoveries in that field? Or, conversely, did the technology emerge independently of the science through assiduous tinkering and trial-and-error experimentation of engineers, with the related science emerging subsequently? Secondly, in addition to the question of historical sequence, we seek to gain insight about the practical or causal influence of one—either technology or science—on the other. In other words, insofar as the practical influence of one on the other may be observed, in which direction does that influence flow?

Our general conclusion, as elaborated in the following analysis, is that—in contrast to the popular belief outside the domain of academic STS studies that technology is generally built on the foundations of science, or that technology is nothing other than "applied science"—technology may emerge independently of science and may in fact be a stimulus for the emergence of science. In short, technology typically comes before science, and may do so more often than is generally presumed to be the case. We label this idea the hypothesis of "*technology-conditioned science*." According to this hypothesis, while in most technological fields there may be a bi-directional relationship between science and technology in the process of technological change, with science providing useful knowledge and stimulus for the development of technology, in most cases the impetus nevertheless arises primarily from

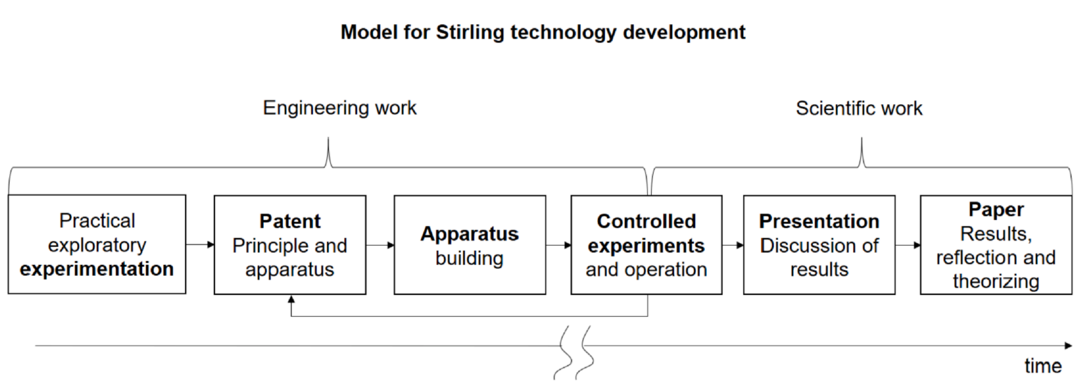

Fig. 1. Sequence of Early Stirling Technology Development.

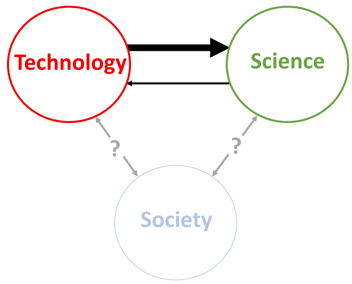

Fig. 3. Technology-conditioned Science.

technology rather than science. As illustrated in Fig. 3, according to the hypothesis of *technology-conditioned science*, the timing and degree of the influence is weighted more strongly in the direction of technology to science rather than the other way around.

While in this paper we focus our attention on the technology-science axis, we of course recognize that science and technology do not exist in a vacuum. Society is the water in which both technology and science swim. However, here we are more interested in understanding the dynamics of the swimming itself rather than comprehensively describing the influence of the water on the swimmers. The interpretation of our empirical research in this paper will therefore incorporate some consideration of the social context (which includes business and economic context) of energy-conversion technology, but a full treatment of that subject must be left to another study.

Our study requires some definitional acuity. The academic literature on the meanings and definitions of the terms "science" and "technology" is voluminous [45–60]. Engaging in a thorough review of the pertinent literature is beyond the scope of this paper, but to ensure conceptual clarity, and informed by the extant literature on the subject, we define our key terms here as follows. *Science* is the "use of evidence to construct testable explanations and predictions of natural phenomena, as well as the knowledge generated through this process" ([61], p. 10). *Technology*, in contrast, is the ensemble of artifacts or systems of artifacts that are intended to function as means towards the attainment of predetermined ends ([62], pp. 178–179). Thus, science is a domain of human activity aimed at generating knowledge about natural phenomena, and it may also be seen as the accumulated knowledge that results from that activity. Technologies, on the other hand, are human inventions that operate as means towards attaining practical outcomes. Technologies are begotten through intuitive and iterative trial-and-error experimentation where real-world results are the primary source of objective knowledge. Science may generate knowledge about technology, and science and technology may influence each other, but technology is ontologically distinct from science. While we recognize that the range of subject matter included as the legitimate subject matter of "science" may vary between academic cultures and communities, and while engaging in a full debate about this matter is beyond the scope of this paper, we employ the term "natural phenomena" here to include any physical or social phenomena that may be classified as natural rather than supernatural.

4.1. Models of science, technology and society

Our hypothesis of *technology-conditioned science* was developed abductively through analysis of both the STS literature and our analysis of the history of Stirling thermodynamic cycle energy-conversion technology. The literature on the technology-science-society relationship may be grouped in to four main schools of thought, each represented by a distinctive theoretical model, which we label respectively as: the *Linear Scientific Impact* model, the *Technological Determinist* model, the *Social Constructionist* model, and the *Holistic Science-Technology-Society* model. The hypothesis of *technology-conditioned science* may be seen as a partial elaboration of a variant of the *Holistic Science-Technology-Society* model.

4.2. The Linear Scientific Impact Model

The Linear Scientific Impact Model is a theoretical formalization of a popular truism that is presupposed by the majority of commentators outside the professional domain of STS studies, including those active in academic research in science and engineering. It is symbolized by the fact that the phrase "science and technology"—rather than "technology and science"—rolls spontaneously off the tongues of analysts, discussants, policymakers and practitioners. It is also reflected in the fact that the default definition of technology, in the minds of even most educated people, is "applied science," a presumption that is reinforced by various dictionary definitions of technology. For example: technology is the "practical, especially industrial, *use of scientific discoveries*" [63]; technology is "the *application of scientific knowledge* to the practical aims of human life" [64]; "Technology refers to methods, systems, and devices which are the *result of scientific knowledge* being used for practical purposes" [65]; or technology is "… the *application of science*" [66] [italics added for emphasis]. The essence of the Linear Scientific Impact Model is the presumption that advances in scientific knowledge in a field eventually lead to concomitant technological advances in that field which, in due course, generate social benefits (or at least social and economic impacts). This idea is illustrated in Fig. 4, where the relationship between science and technology is presumed to be a linear process.

The best known, and perhaps most influential, published example of the Linear Scientific Impact Model is the July 1945 report to the President of the United States (Franklin D. Roosevelt) by Dr. Vannevar Bush, then the Director of the U.S. Government's Office of Scientific Research and Development. Aptly titled *"Science – The Endless Frontier"* [67], the report ended with a recommendation to the President and the U.S. Congress for the creation of the National Science Foundation, a proposal that came to fruition in the early 1950s. Examples of the underlying logic of the report and the practical initiatives of the U.S. Government that ensued may be seen in the following quotes ([67], p. 7):

> The most important ways in which the Government can promote industrial research are to increase the flow of new scientific knowledge through support of basic research, and to aid in the development of scientific talent.

> The responsibility for the creation of new scientific knowledge—and for most of its application—rests on that small body of men and women who understand the fundamental laws of nature and are skilled in the techniques of scientific research.

While the creation of the National Science Foundation was clearly motivated by a desire to stimulate practical developments in technology, industry and the economy—rather than only the noble pursuit of curiosity-driven science—it is also clear that the underlying philosophy of Bush and his compatriots in the U.S. Government embodied the idea of the "linear impact of science" on technology and society.

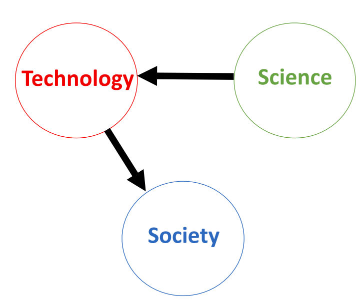

Fig. 4. The *Linear Scientific Impact* Model.

Despite its common-sense appeal and widespread acceptance, the Linear Scientific Impact Model has come under pressure. For example, a recent proposal from the U.S. Congress—with the purposefully reminiscent title of "The Endless Frontier Act"—aims to expand the funding of the National Science Foundation by 100 Billion U.S. Dollars, but with a name change, to the "National Science and Technology Foundation," and an explicit expansion of its mission to include *technological* research and development, under the auspices of a newly created Technology Directorate within the Foundation [68]. This initiative of the U.S. Government signals a possible shift of thinking amongst policymakers towards recognizing technology as a primary domain of public investment in its own right, rather than as a subsidiary domain or follow-on domain of science.

Academic criticisms of the Linear Scientific Impact Model have also been appearing from at least the mid-1960s [54,69]. Agassi, in particular, questioned the idea of technology being nothing more than applied science, and he even pointed to the possibility of science being dependent upon technology. For example, he wryly wrote about "technology created for the purpose of enabling pure scientific research to proceed …" ([55], p. 98). Since then, other scholars have echoed the insights of Agassi, observing that the direction and channels of the relationship between science and technology are far more complex than assumed by supporters of the Linear Scientific Impact Model (e.g., [50,59,70–75]). The conclusions of de Solla Price ([59], p. 6) are representative and presaged the new wave of thought that began to flourish from the 1980s onwards:

> At all events, the history of technology, though a complex mixture of cumulative advance and unexpected innovations, all subject to considerable interaction with market forces, does not seem strongly dependent on science. There is no general way in which one can add technological footnotes to a step-by-step history of science, and there is no general way in which one can write a preface to the history of science for each chapter of a history of technology.

In the wake of the pioneering contributions of Agassi [54,55], Bunge [69], de Solla Price [59], Brooks [70] and others, three distinct schools of thought encompassing three distinct models, may be discerned that challenge the tenets of the Linear Scientific Impact Model, namely, the Technological Determinist Model, the Social Constructionist Model, and the Holistic Science-Technology-Society Model. We will now briefly consider each of these before elaborating and empirically testing the hypothesis of technology-conditioned science.

4.3. The Technological Determinist Model

The idea of technological determinism is most closely associated with the ideas of the French sociologist, Jacques Ellul [76,77], whose publications gained influence in the English-speaking world at around the same time that Agassi's critiques of orthodoxy appeared. Ellul ([77], p. 233) articulated his core concept as follows:

> Everything takes place as if the technological phenomenon contained some force of progression that makes it move independently of any outside interference, of any human interference, of any human decision … The technological phenomenon chooses itself by its own route … [If] man produces the self-augmentation of technology (which could not generate itself, of course), he does so by assuming only an occasional and not a creative role. He cannot help but produce this augmentation; he is conditioned, determined, destined, adjusted, and preformed for it.

While in this quote he seems to be concerned primarily with the evolutionary dynamics of technology itself, and with the relationship between society and technology, rather than with the relationship between science and technology, it is apparent when one reads all of his work that Ellul sees science as a human activity that is caught up in the "technological phenomenon" (translated from the original French term, *"La Technique"*) just as much as other domains of human activity. There are two aspects to Ellul's understanding of the evolution of technology in society: first, that technology progresses inevitably according to its own gradually unfolding internal technical logic; and, second, that as technology evolves, society itself takes on technical characteristics and, thus, becomes the "technological society." In other words, the social context of technology becomes technological, thereby reinforcing the internally driven technical logic of technological evolution. This phenomenon is sometimes also referred to as "autonomous technology" [78].

The concept of technological determinism is illustrated in its most simple form in Fig. 5-A. Many other writers besides Ellul have articulated a concept along these lines. Some [79–85] describe the emergence of technological determinism or autonomous technology in society critically, with pessimism, while others [86–91] appear to embrace it with optimism or even alacrity, and others [74] describe the phenomenon but refrain from broad, judgmental normative assessments. It is beyond the scope of this article to fully survey the pertinent literature. Rather, our key observation here is that the plausibility of the Linear Scientific Impact Model has been challenged in the academic literature, not only by critical scholars such as Agassi [54,55], de Solla Price [59], Brooks [70] and their like, but also by its intellectual antithesis in the form of the Technological Determinist Model.

More recently, theories such as "technological parasitism" have emerged in the literature, accompanied by sophisticated techniques for analyzing and forecasting the direction of technological evolution [92,93]. In this variant of the Technological Determinist Model (Fig. 5-B) the focus is on technology as such, with the majority of attention directed towards the inner dynamics of technological change [74], and with little or no substantive analysis of the dynamics of science and society. In another variant (see Fig. 5-C), science is bundled together with technology, rather than society, in a quasi-amorphous world of "technoscience" [57,94–99]. While this newer literature may not always exude the rhetorical temper associated with the early protagonists of technological determinism, it shares its belief or presumption that technology evolves as a system, according to its own inherent logic, and that while it evolves within society (and thus, of course, draws upon the resources of science and the economy) technology's natural evolution is not determined by its social context.

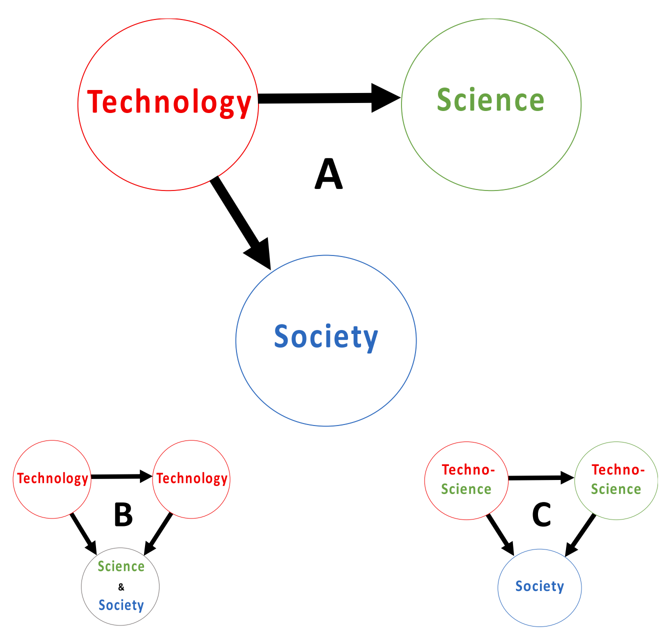

Fig. 5. The *Technological Determinist* Model.

4.4. The Social Constructionist Model

The second major school of thought that has challenged the tenets of the Linear Scientific Impact Model may be labelled loosely as "social constructionism," and is illustrated in its most simple form in Fig. 6. There are two main variants of the social constructionism, one focused on the social construction of science [100–103] and one focused on the social construction of technology [13]. Much of the literature on the social construction of technology coincidentally also addresses the topic of the social construction of science, so for the purposes of this paper it will be sufficient to focus our attention on the social construction of technology. For examples of critical assessments of the social construction of science literature, as such, see Murphy [104] and Kidner [105].

The origins of the Social Constructionist Model may be found in academic literature from the early 1960s onwards, in the works of sociologists such as Berger and Luckmann, who introduced the term "social construction of reality" [106], and economists such as Jacob Schmookler [11] who argued that "technological progress is not an independent cause of socio-economic change, and an interpretation of history as largely the attempt of mankind to catch up to new technology is a distorted one" ([11], p. 1). This line of thinking subsequently developed in to a widely discussed school of thought exemplified in the writings of scholars such as Latour and Woolgar [107,108] and Collins [109–111]. However, this school of thought is generally associated closely with the work two decades later of Pinch and Bijker, who argued that "both scientific facts and technological artefacts are to be understood as social constructs" ([12], p. 399). Their conclusions were supported by research on the development of both solar energy technology and bicycle technology. Pinch and Bijker's research was later augmented by further research along similar lines during the 1990s in technological fields such cement, glass and mini computers [112], nuclear missile guidance systems [113], supercomputing [114], telephony [115], information technology more generally [116], and, biotechnology, ceramics, and parallel computing [117]. By the late 1990s a number of general theoretical or conceptual studies in this genre were published [118,119], signaling that the Social Constructionist Model had moved from academic heterodoxy to orthodoxy [13,120]. Williams and Edge ([118], p. 875) summarized the Social Constructionist Model as one that conceives of technological innovation as a "complex social activity: an iterative, or spiral process that takes place through interactions amongst an array of actors and institutions involved and affected."

The school of thought associated with the Social Constructionist Model has continued to develop since the turn of the century, both thematically and empirically [121–127], signaling the resilience of intellectual opposition within the academy to both the Linear Scientific Impact Model and the Technological Determinist Model. Social constructionism has arguably provided a useful counterbalance to the biases, or limited perspectives, of both of these models. Nevertheless, it has not escaped criticism [128]. A key problem with the Social Constructionist Model (or at least with a crude or a simplistic interpretation of the model, especially its early manifestations), however, is that while it is supported by many studies which demonstrate that neither technology nor science is socially neutral, it is difficult to deny the weight of evidence that both technology and science nevertheless influence society in a variety of ways, and that something corresponding to the phenomenon of "autonomous technology" may be observed in the relationship between technology, science and society [74,75,80,92,129–131]. In the words of Geels ([132], p. 904):

> Technologies have a certain 'hardness' or [obduracy], which has to do with their material nature, but also with economic aspects … This hardness also implies that artefacts cannot entirely be shaped at will. Although I am sympathetic about social construction of technology… there are limits to the interpretative flexibility of artefacts. Technical possibilities and scientific laws constrain the degree to which interpretations can be made. Next to social shaping, there is also technical shaping …

The other key problem with the Social Constructionist Model is arguably that while it provides a useful antidote to the theoretical limitations of the other two models, it provides little in the way of practical guidance for managers and policymakers to address the purported ills of the technological society ([129], pp. 375–376). In their general opposition to the idea of technological determinism, the original agenda of protagonists of the Social Constructionist Model may have been primarily intellectual rather than managerial or strategic, and perhaps this problem with the Model therefore ought not to be viewed as a significant shortcoming. However, as the school of thought associated with Social Constructivism has evolved, leading exponents of the school such as Bijker [13] have elaborated its core ideas and arguments thoughtfully in way that, while maintaining a relativistic and contextual approach to the analysis of the development of technology, has acknowledged the impact of technology on society and the "development of social institutions as constituted by technology" ([13], p. 71). This thematic development may presage the emergence of a greater managerial or policy orientation, or a deeper practical interest in the craft of engineering, amongst protagonists of Social Constructionism to augment the school's original intellectual project?

While acknowledging the limitations of all three models—the Linear Scientific Impact Model, the Technological Determinist Model and the Social Constructionist Model—we are led to conclude that simply choosing one of them will not be satisfactory, either theoretically or empirically, or from the vantage point of praxis. A more comprehensive and robust model is arguably required.

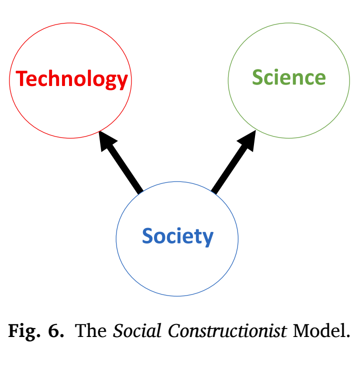

Fig. 6. The *Social Constructionist* Model.

4.5. The Holistic Science-Technology-Society Model

The Holistic Science-Technology-Society Model is based on the recognition that each of the three models just summarized embodies plausible and, in most instances, defensible observations about the relationships between technology, science and society. In its most simple form, pictured in Fig. 7-A, it embodies the idea that each of the three focal domains of the science, technology and society enigma is characterized by a bidirectional relationship with each of the other two domains.

In some ways, this model appeals to common sense, but is also embraced in one way or another by a variety of academic researchers and commentators [131,133–135], including both those who may be labelled as sympathetic critics of the Social Constructionist Model [129] and some whose writings originated in the Social Constructivist school of thought [13]. It is also presaged by the well-established school of thought associated with socio-technical systems theory [136–141]. Some variations of the Holistic Science-Technology-Society Model are shown in examples B, C and D of Fig. 7, according to which domain is believed to be dominant in the triangle of bi-directional relationships, and according to which direction the influence is believed to be the strongest. However, all are united by the idea that technology, science and society—while each representing nominally discrete

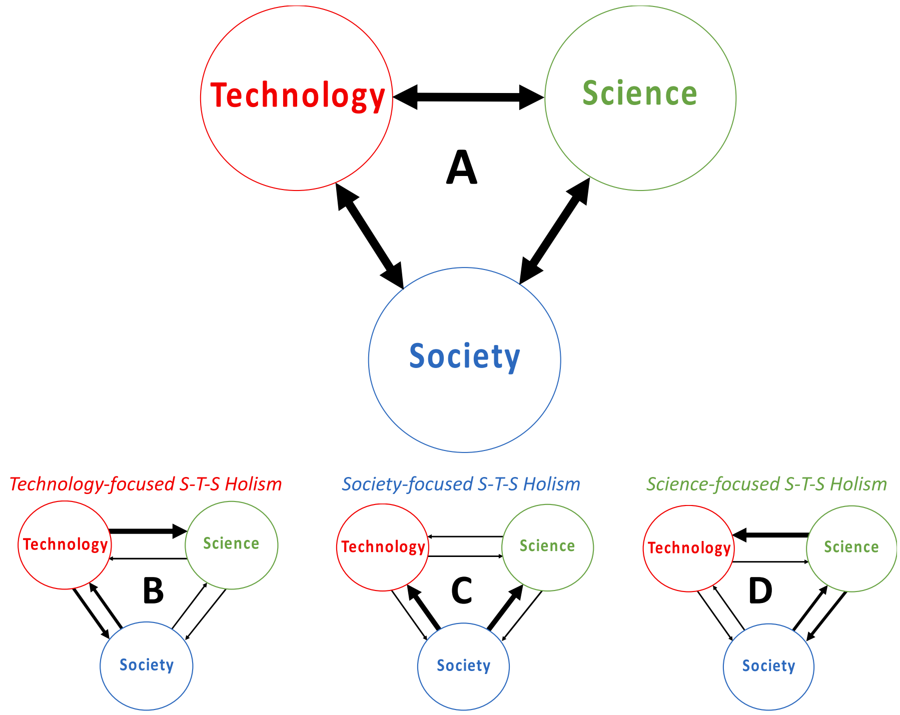

Fig. 7. The *Holistic Science-Technology-Society* Model.

vectors—influence each other and also co-evolve.

4.6. The hypothesis of technology-conditioned science

Our hypothesis of technology-conditioned science (see Fig. 3) is a variant of the Holistic Science-Technology-Society Model and which, while not directing much analytical attention to the "society" domain in the triad, nevertheless acknowledges its importance but focuses attention on the technology-science axis, and holds that—in contradistinction with the Linear Scientific Impact Model—the timing and degree of the influence is generally weighted more strongly in the direction of technology to science rather than from science to technology. In short, it holds that, usually, technology comes first.

While the hypothesis of technology-conditioned science almost certainly goes against the (typically unexamined) presumptions of most contemporary scientists, it nevertheless has a respectable academic pedigree dating back more than three decades [58,59,70,142–150]. Some [151,152] stress that there is typically a two-way mutually-reinforcing relationship between technology and science, and argue that it is often difficult to differentiate between science and technology—especially in contemporary fields such as biotechnology and bioscience—but nevertheless observe that, in view of the available empirical evidence, the old presupposition that "technology is applied science" is simply untenable. Brooks, an early advocate of what we label here as the hypothesis of technology-conditioned science, expressed it aptly ([70], p. 477):

> The converse impact of technology on science is of at least equal importance: (1) through providing a fertile source of novel scientific questions and thereby also helping to justify the allocation of resources needed to address these questions in an efficient and timely manner, extending the agenda of science; (2) as a source of otherwise unavailable instrumentation and techniques needed to address novel and more difficult scientific questions more efficiently.

This conclusion echoed similar observations from a decade earlier by de Solla Price ([59], p. 15), who averred that "the dominant pattern of science/technology interaction turns out to be that both the scientific and the technological innovation may proceed from the same adventitious invention of a new instrumentality."

Finally, one of the most important empirical studies of the relationship between technology and science is the historiographical tome of McClellan and Dorn [142], in which the joint and separate histories of technology and science are traced from the prehistoric era to the present, and in which it is shown that in most historical situations prior to the twentieth century science and technology progressed in either partial or full isolation from each other, both intellectually and sociologically. In the words of McClellan and Dorn ([142], p. 2), who contrast their conclusions with what they see as the dominant contemporary orthodoxy:

> … a more accurate historical appreciation of technology will place proper emphasis on independent traditions of skilled artisans whose talents crafted everyday necessities and amenities throughout the millennia of human existence. Such a historical reappraisal will also show that in many instances technology directed the development of science, rather than the other way around.

In citing these sources here our purpose is to show that, while perhaps not representing the majority view, our hypothesis of technology-conditioned science has substantial support in the academy. Hence, rather than devote additional time to theory-oriented scholarship, our primary focus for the balance of this paper will be on adapting this hypothesis to the development of energy-conversion technologies and testing the generalizability of the hypothesis through empirical research.

Our systematic survey of the STS literature has revealed that our pre-search hypothesis may be reformulated into a formal research hypothesis, which we label here as the "technology-conditioned science" hypothesis. Thus, we hypothesize that *the timing and the degree of influence of technology and science in the development of energy-conversion technologies is generally weighted more in the direction of from technology to science than from science to technology*. To test this hypothesis, we examine the evolution of the Stirling engine and the Stirling refrigerator during the second half of the Twentieth Century and the early Twenty First Century. Our method, to be elaborated below in Section 5, will be to trace the development of both the scientific/scholarly literature and the patent literature for both of these fields of technology during the pertinent time periods. Our analysis will be based on the proposition that academic publications are predominantly an indicator of activity in the sphere of science, while patents (which are also a type of publication) are predominantly an indicator of activity in the sphere of technology.

5. Methodology for data analysis

How might the theory of technology-conditioned science be tested? The pre-search hypothesis from the analysis in Section 3 of two cases of Stirling technology development and the resulting theory from our STS literature survey in Section 4 predict that the timing and degree of influence between technology and science are generally weighted more strongly in the direction of technology to science than in the other direction. However, to empirically test the generalizability and robustness of our theory, we need to address several methodological questions. First, what indicators are appropriate for representing science and technology? We argue that academic publications are predominantly indicators of activity in the sphere of science and that patents (also a type of publication) are predominantly indicators of activity in the sphere of technology.

Second, how may the form and direction of the link between science and technology be measured? As suggested by the historical examples discussed in Section 3, a suitable unit of analysis for this purpose is written knowledge, in the form of a published document (either a patent or a scientific/academic publication) that is accessible by participants in each of the two domains. We further assume that the migration of knowledge between patents and academic papers may, in principle, move in both directions, and that confirmation of the knowledge transfer may be obtained through the analysis of annual publication trends.

Third, what are the predictions that we may propound to test the generalizability of the hypothesis of technology-conditioned science? Our main prediction is that patenting activity precedes the publishing of scientific papers.

5.1. Patents and scientific papers as indicators of technological and scientific activity

The approach we have adopted here, of treating papers as representations of science and patents as a representation of technology, is typical of studies that analyze the relationship between science and technology [152]. Some commentators [153] have criticized this approach for purportedly being reductionist and a-contextual. One way of addressing that criticism is to engage appropriate subject-matter experts and stakeholders to analyze each document carefully, to add contextual information to help interpret and more accurately characterize each document. The work of Hane and Hutchinson [154] is an excellent example of how such an approach has been applied in the analysis of Stirling technology development to ameliorate potential problems of interpretation. Nevertheless, while we are aware of the limitations of relying solely on patents and academic publications as indicators of technological and scientific activity, respectively, we decided against conducting an extra phase of research employing a range of subject matter experts to conduct contextual analysis. Limitations of time and other resources made it impractical. However, we mitigated these limitations by our own careful study of the content of the individual scientific papers and patents to take contextual factors in to account, as far as was feasible, in the classification of documents. This secondary layer of analysis, combined with the fact that one of the authors is a technical subject matter expert on Stirling technology, makes our adopted approach sufficiently rigorous for our purposes.

Our data on academic literature were extracted from a leading academic indexing database, *Scopus*.[1] We extracted all scientific journal papers concerned with Stirling technology indexed in *Scopus* over the almost six decades from 1960 to 2018. We included only verified peer-reviewed scientific journal publications, and carefully filtered out all other categories of documents, such as conference papers, conference presentations, conference reviews or technical reports. In short, we manually excluded all types of documents that either could not be classified as peer-reviewed scientific papers, or that came from sources whose provenance or authenticity could not be verified as credible peer-reviewed scientific journals. Our data set excluded classified (i.e., secret) research, which by definition, was not available in the public domain. One limitation of the data set is that it most likely understates scientific literature that was neither published in English nor translated in to English. Despite these limitations, our final data set of academic publications is arguably a robust and credible representation of the evolving global scientific state of the field.

The data for the analysis of patent activity were drawn from two databases, *Scopus* and *Cipher*.[2] The patent data from the *Scopus* database have some limitations. First, *Scopus* does not categorize patent documents by either country or organization. Second, *Scopus* does not differentiate between patent applications and granted patents. Furthermore, the unit of analysis for patents in the *Scopus* database is any patent document registered in patent offices, rather than a patent family, which includes patents for the same inventions filed in different countries. This approach may cause the double-counting of patented inventions from the same family. The patent data from *Scopus* were therefore used only for the evolutionary analysis of patent activities over time. The *Cipher* database, on the other hand, enables careful categorization of patent documents according to country, organization (assignee), and patent family; and, importantly, *Cipher* includes comprehensive patent data worldwide. However, *Cipher* provides data for patents from 1980 onwards only. Comprehensive data on granted patents are available from 2000 to 2020, but, due to the 18-month embargo by patent offices on the publication of patent applications, data on applications are available only up to 2018. For consistency we therefore limited our final analysis of the data sets to the year 2018 rather 2020. In building our patent data set we relied upon *Scopus*-sourced data prior to 1980 and *Cipher*-sourced data from 1980 onwards.

We also created a third database, consisting of conference papers and presentations, also sourced from *Scopus*. We carefully checked the *Scopus* data source to manually filter out all document sources that were not classifiable as conference proceedings. Our logic for building this third database was that conferences may arguably be portrayed as a kind of hybrid environment in which "technical chatter" takes place during the early phases in the development of a field, or sub-field, and where both engineers and scientists may engage in discussion before the dominant scientific paradigms of the field are generally visible. Conference papers—which often are subject only to quasi peer-review processes, review processes with low levels of rigor, or no peer-review processes at all—may not be treated as robust indicators of quality scientific research, but may nevertheless provide a useful window through which early experimental or trial-and-error phenomena or results may be observed.

For search inquiries, in building all three databases, we applied common terminology used in the domains of Stirling engines and refrigerators. For Stirling engines, we used the search term "Stirling engine." For Stirling refrigerators, we used a combination of terms that reflect varying terminology in the field: "Stirling AND (refrigerator OR cooler OR cryocooler OR "heat pump") AND NOT "Stirling engine"." Having described the indicators for science and technology employed in

[1] *Scopus*, Elsevier B.V., http://www.scopus.com.

[2] *Scopus*, Elsevier B.V., http://www.scopus.com ; *Cipher*, Aistemos Limited, https://cipher.ai.

this study, as well as the data sources upon which we relied to build our three databases, we will now discuss the issue of identifying the exact form of the relationship between the domains of science and technology.

5.2. Forms and direction of the relationship between science and technology

Drawing upon the literature on knowledge transfer [155], we conceptualize knowledge transfer as a process by which a unit of knowledge from an external source is internalized, either in part or in full, by a recipient. Both the scientific domain and technological domain may take the role of either the source or the recipient (or both) of knowledge. In the historical examples of Stirling engines and refrigerators discussed in Section 3 we observed that the transfer of technical knowledge between the engineering and scientific domains may take place in the form of information articulated in published documents.

What are the appropriate units by which knowledge transfer may, in principle, be measured? Knowledge may be transferred in at least four forms: graphical (written or drawn) in documents, verbal (by either informal communication or the transfer of individuals), demonstrated action (typically by the transfer of individuals), and physical (e.g., in a scientific apparatus or technological device) [156]. In this study we considered only the first form, namely, documents, because it is the only form for which we were able to obtain reliable data in our chosen technological field over the whole time-period and geographical scope of our inquiry. We excluded verbal and direct action-based transfer of knowledge because of the impossibility of recording such knowledge transfer for the historical, organizational and geographical scale of our project. Notwithstanding this constraint, and on the assumption that conference papers may be treated as an analogue of knowledge transferred verbally during conferences, we propose that conference proceedings may serve as an indirect indicator the essence of the verbal transfer. For pragmatic reasons, we were unable to include analysis of knowledge embodied in physical objects as a unit of knowledge transfer.

The graphical form for transferring knowledge includes patents, scientific publications, and other technical writings. We propose that patents, peer-reviewed journal papers, and conference papers together may be treated as representing—with an acceptable level of accuracy—the units of all transferred technical knowledge between the engineering and scientific domains. In other words, if knowledge is transferred from science to technology, or from technology to science, then it takes place through the vehicle of published documents, even if it sometimes also takes place directly without the medium of published documents, or in a hybrid manner at conferences where the communication takes place both informally and formally. This proposition allows us to test the theory using bibliometric data for both academic papers and patents. Our primary layer of analysis is the relationship between patents and published scientific journal papers, and our secondary layer of analysis is the relationship between patents and conference presentations.

How may we establish that there is any connection or direct influence between the scientific and technological domains? Validation of the fact that the transfer of a unit of knowledge between two domains actually took place may be problematic. A standard solution to this problem is the application of citation metrics between patents and scientific papers. This method can be classified into two sub-categories: citation of patents in scientific papers and citation of scientific papers in patents. When speaking of the latter, the evidence from the literature shows that although the contribution of academic research to industrial innovation may have been considerable [157], citation of papers in patents hardly represents a reliable indicator of the effectiveness and efficiency of knowledge transfer between fields [152]. One of the reasons for this situation is the practical strategic nature of a patent. Citing a paper in a patent does not necessarily mean applying scientific knowledge in technology-related activities. Rather, it is typically placed there for legal reasons to define the state of the art in the field, for the analysis of novelty and inventive step. The citation of patents in scientific publications is also a recognized approach to establishing the link between science and technology, but it is still unclear why researchers cite patents [158]. The technical knowledge embedded in a patent is sometimes opaque to those not practiced in the arcane craft of drafting patent claims, but in principle the patent nevertheless represents the state of the art in a field. Although citing papers or patents may characterize—within the limitations discussed—knowledge transfer between domains, it does not describe the transfer from sources that were not cited. While transferable knowledge may flow in both directions between science and technology, analysis of citations in either direction between academic publications and patents is not an adequate method for measuring the overall transfer of knowledge in a particular field or sub-field between the domains.

We have therefore chosen to use an alternative method to investigate the transfer of knowledge, based instead on the evolution, or coevolution, of published documents. Liu and Rousseau [159] demonstrated empirically how scientific publications from one field over time diffuse to other scientific fields. In line with this observation, we propose that published knowledge—in either a set of patents or in a set of academic papers—would diffuse over time into the opposite domain. With an increase in the absolute number of publications, there should be a correlation between the scale of scientific activities and technological activities, due to knowledge diffusion through publication. This correlation may be higher when organizations and geographical locations are proximate [160]. With increasing global access to patents and papers, global diffusion also becomes more potent [161]. The publishing trends for scientific and patent documents should exhibit similarities or observable relationships if a link exists between domains due to diffusion. Confirmation of this phenomenon may be found, for example, in the domains of the nanotechnology industry [162], anticancer products [163] and graphene technologies [164]. In this study, we have therefore adopted analysis of publishing trends as the most appropriate methodology for examining the transfer of knowledge between the domains of technology and science.

To evaluate the publishing trends, we applied three techniques. First, the visual evaluation of trends that showed the evolution of publication activities over the years. Second, the generation of polynomial functions that fit scattered data and approximated patent and paper trends. The polynomials were analyzed using conventional statistical analysis to find the mean and median difference in publication dates. We tested polynomials of different degrees and R^2 values no less than 0.8 to check the robustness of results. Third, to verify the results of the previous technique, we calculated a weighted average publication year for patents and papers. Each year (variable) contributed a different number of publications (weight). By estimating the weighted average year of publications, we found some indicative year that showed when, on average, all patents or papers were published. The difference between the numbers is the time lag.

In summary, our methodology for testing the hypothesis of technology-conditioned science employs bibliometric data for three types of published documents (peer-reviewed academic papers, patents and conference papers) and assumes that:

1. Peer-reviewed scientific journal papers represent science;
2. Patents represent technology;
3. Conference papers represent pre-paradigmatic professional “chatter” and verbal knowledge transfer for both technology and science;
4. Patents, peer-reviewed journal papers, and conference papers together are a reasonable representation of the units of all transferred technical knowledge between the technological and scientific domains;
5. There is a dynamic interplay between scientific and technological activities due to the diffusion of knowledge through publications.

5.3. Predictions from the hypothesis of Technology-conditioned science

Drawing upon the model in Fig. 3 and the main assumptions of our methodology we may formulate the following predictions:

Prediction 1: Patents in a field are generally published earlier than journal papers in that same field.

Prediction 2: During the initial phase of conference paper publishing in a field, patenting activities and conference papers evolve in parallel.

Prediction 3: During the later phases of technology development in a field, patenting activity precedes conference publishing.

Prediction 1 is the main prediction evoked by the hypothesis of technology-conditioned science. If the link between technology and science is generally weighted more strongly in the direction of technology to science, rather than science to technology, then patents should precede journal publications. Conference papers may not be readily classified in either one domain or the other, and may represent a hybrid domain of nascent technology and science. It is not uncommon for engineers to promote their emerging technological work using conference presentations, as we found in the cases of the Stirling brothers and Alexander Kirk. However, we should also expect scientists to present emerging work at conferences. We therefore predict that during the early phase of technology development in a field, publication trends for conference papers (which may contain either or both technological and scientific content) and patents may emerge without a clear “leader and follower” pattern (Prediction 2). However, we expect that over time, as a field begins to mature, the contribution of scientists to conference publications would become more prominent as a result of knowledge diffusion. In this case, similar to the case of Prediction 1, according to the hypothesis of technology-conditioned science, conference papers should start following patent publications (Prediction 3).

6. Results of statistical data analysis

Table 1 summarizes the results of our systematic efforts to build data sets of published documents from 1960 to 2018 related to the fields of Stirling engine technology and Stirling refrigerator technology. The set that we have labelled as “Patent Documents” is a combination of published patent applications and granted patents. Thus “Published Patent Applications” is a sub-category of “Patent Documents (all types).”

Figs. 8 and 9 respectively depict results for the Stirling engine and Stirling refrigerator. The left side of both figures depicts the comparison between peer-reviewed journal papers and all published patent documents. The right side exhibits the comparison between published conference papers and patent applications. The absolute number of published documents varies considerably between each basic publication category—namely, published patent applications, granted patents, scientific journal papers and conference papers—and hence comparing raw numbers from each category on the same graphical scale is impractical. To compare the degree of publication activity for each type of document we therefore normalized the absolute number of documents per year by the maximum absolute number per year over the studied period.

6.1. Results for the Stirling engine

Fig. 8-a shows clearly how patenting activity started leading scientific research from the beginning of the 1970s. The mean time lag between patent and scientific trends is 6.1 years, the standard deviation is 3.5 years, and median time lag is 5 years. The weighted average year of publications for patent documents is 2004 and for scientific papers is 2007, with the time lag of 3 years. This result confirms Prediction 1, supporting the proposition that in the field of Stirling engine technology the dominant direction of influence is from technology to science.

Fig. 8-b reveals that a significant number of conference papers in the field of Stirling engines started appearing at the beginning of the 1980s and evolved in parallel with patent applications until around 2000. This outcome confirms Prediction 2: during the early phase of the field’s development conference papers consist mainly of engineering results and thus vacillate concurrently with patent applications. In the 1980s, we also see that patent publications, along with conference papers, exhibited a temporal jump, which indicates an intensification of general activity in this field in the 1980s. We will discuss possible reasons for this phenomenon shortly.

From 2000 onwards, however, patent applications have led conference papers, thus confirming Prediction 3. As the participation of scientists in the field increased over time the content of conference papers became more scientific in character, and thus the relationship between conference papers and patents became more like the relationship between academic journal papers and patents observed in Fig. 8-a, with patent applications leading conference publications.

6.2. Results for the Stirling refrigerator

Fig. 9-a reveals that in the field of Stirling refrigerator technology patenting activity started leading scientific research from the mid-1960s onwards. The mean time lag between patent and scientific trends is 6.4 years, the standard deviation is 2.6 years, and median time lag is 7.6 years. The weighted average year of publications for patent documents is 2002 and for scientific papers is 2005, with the time lag of 3 years. This confirms Prediction 1 and supports the proposition that the dominant direction of influence is from technology to science in both fields of Stirling technology.

In contrast with the case of Stirling engines, however, we do not observe a similar temporal jump in patenting activities for Stirling refrigerators during the 1980s, but rather an organic linear growth beginning around 1980. Fig. 9-b shows that intensive conference work in this field also emerged around 1980. This year seems to be decisive in the development of both technological domains, a phenomenon which will be discussed below. Our data for Stirling refrigerators do not reveal a clear leader-follower relationship between conference papers and patent applications. This result confirms Prediction 2. However, in contrast with the case of Stirling engines, we do not find confirmation of

Table 1
Profile of Publication Data Sets.

Document Type	Publication Parameters of Each Type of Document			
	Stirling Engine Technology		Stirling Refrigerator Technology	
	Total Number 1960-2018	Maximum Annual Number	Total Number 1960-2018	Maximum Annual Number
Published Journal Papers	996	90	499	35
Patent Documents (all types)	9088	530	7126	326
Published Patent Applications	3224	156	1148	94
Published Conference Papers	1428	91	585	41

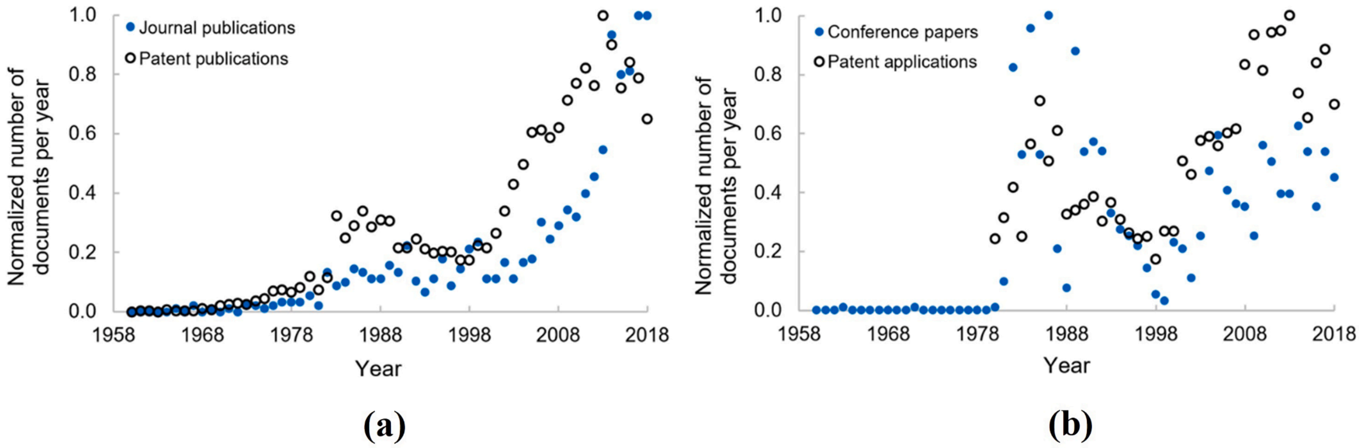

Fig. 8. Normalized Scientific and Patent Activity for the Stirling Engine. (a) journal and patent publications, (b) conference papers and patent applications.

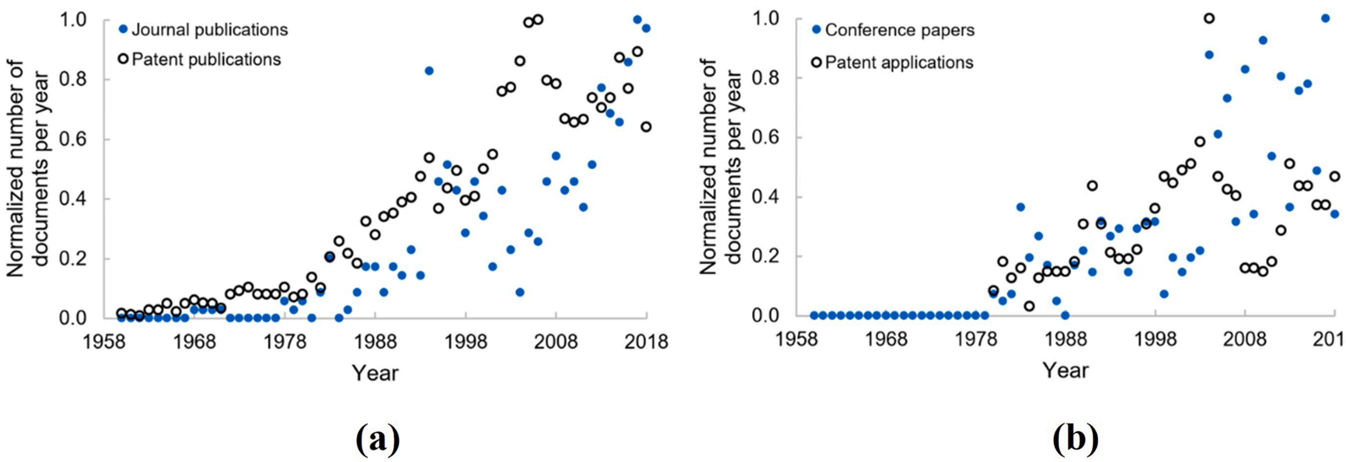

Fig. 9. Normalized Scientific and Patent Activity for the Stirling Refrigerator: (a) journal and patent publications, (b) conference papers and patent applications.

Prediction 3. The volumes of patent applications and conference papers keep evolving in parallel until the end of 2018. This outcome might be explained by the fact that the field of Stirling refrigerator technology is relatively young. The total number of journal publications related to Stirling refrigerators is about half that related to Stirling engines (see Table 1). The equivalent proportion for conference papers in the field of Stirling refrigerators is two fifths and for patent applications it is about one third (Table 1).

In short, our data for scientific and engineering activity in the fields of Stirling engines and Stirling refrigerators confirm that patenting (as an indicator of technological activity) precedes academic publishing (as an indicator of scientific activity), thereby verifying our theory that technology comes first and that technology conditions scientific activity. The evolution of this relationship is not trivial. Patenting activity emerges first, followed later by technical conference "chatter," which subsequently evolves into the growth of scientific work conditioned by patenting activities.

7. Discussion

7.1. Counter-intuitive Results?

In a recent study by Dernis et al. [165] that applied a text-mining methodology, the authors studied the bursting of new topics in patent applications and scientific papers and found a statistically significant and "somewhat surprising" result. In 17 fields of technology analyzed between 1990 and 2011, patent filings tended to predate scientific publications on average by 18 months. The difference depended on the technological area and ranged from 2–3 years in nanotechnology to almost simultaneous publishing in information and communication technology. Dernis et al. offered three possible explanations for this phenomenon: (i) researchers have to go through a lengthy peer-review publishing process; (ii) researchers patent first to maximize chances of commercialization; and, (iii) academic researchers spend more time improving a manuscript before submission to a journal than inventors and their agents spend improving a patent application before submitting it for examination. The last two explanations, while they might be superficially plausible, are undermined by the empirical evidence that researchers and inventors are typically different people [152] and by the fact—as reflected in the academic cliché, "publish or perish"—that academic competition pressures researchers to publish as soon as possible, and motivates them to increase their rates of publishing [166].

The first explanation offed by Dernis and her colleagues—for their "unexpected" result that patents typically precede scientific journal publications—deserves more discussion. If an academic journal paper manuscript and patent application on the same topic were *submitted* at the same time, the priority date of the patent application would be earlier than the paper publication date by the length of time it would take for the peer-review process to be completed. According to Dernis et al. this lag between the submission date and the publishing date of journal papers may create a false impression that work embodied in patents predates work embodied in scientific papers. However, notwithstanding the fact that there is an 18 month lag between the filing and publication of patent applications, and that several years may also pass between the filing of an application and the grant of a patent, the available empirical evidence goes against the explanation offered by Dernis et al. Statistical analysis published by Björk and Solomon [167] shows that the length of the peer-reviewed publication process in technical fields ranges between 9 and 13 months, with the average being 10.5 months. This figure does not fully explain the apparent anomaly of 18 months difference between patent filings and paper publication. The empirical evidence reveals that, on average, the bursting of patent filings occurs about 7 months earlier than the bursting of scientific manuscript submissions.

The explanations offered of Dernis et al. are also weakened by the fact that they did not differentiate between conference papers and journal papers in their research. As was shown in the results section of this paper, at early stages of technology development, scientific publications consist mainly of conference papers that often better represent the technological domain rather than the scientific domain. This means that if journal papers only were used in the statistical samples, the average time difference between the patent filing and journal paper submission would exceed 7 months. The explanations offered by Dernis et al. do not justify their attempt to explain away the counter-intuitive statistical results of their own research rather than take them as indicators of the underlying empirical reality. The fact that they were surprised by their results, and sought to explain them away as statistical anomalies, may be interpreted as evidence of their tacit adherence to the paradigm of the orthodox *Linear Scientific Impact Model* rather than the hypothesis of technology-conditioned science advocated by the current authors.

7.2. Implications of results

The results of this study enrich our understanding of the evolution of science-intensive technologies and highlight the mechanism whereby patents may typically predate academic papers on the same topic. This understanding draws on the historical example of the invention of Stirling technology (Section 3) and on the analysis of many scientific and patent publications in two different but complementary technological fields. The invention of science-intensive technologies—at least in this particular technological domain—begins with trial-and-error experimentation and many iterations of prototype design, in the context of practical problem solving, rather than with scientific research. This experimental work might be hidden from the public for many years before the results are tested in a real environment, and patented and summarized in conference papers. Conference "chatter" makes findings available for the public in technological and scientific domains, and catalyzes further work. This period of idea fermentation may take several decades, igniting work in both domains and attracting more participants into the field. The conferences play a catalytic role in this process. As the number of participants entering the field increases, the total publication activity builds up. However, the evolution of this activity still abides by the principle of technology-conditioned science, in

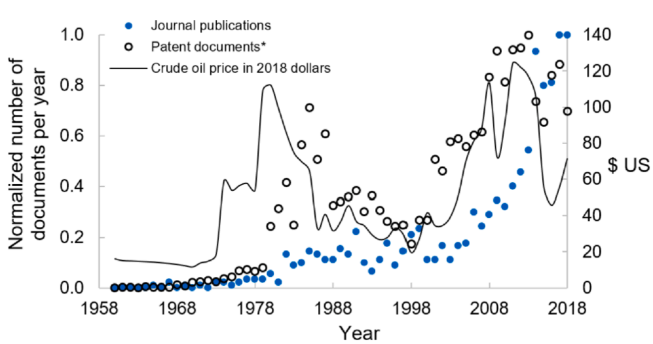

Fig. 10. Effect of Oil Prices on Publishing Activity *Patent applications after 1980 and patent documents (all types) before 1980.

which patent activity emerges earlier than scientific papers. Fig. 7 provides a helpful visualization of this process.

As discussed earlier, the year 1980 was a pivotal point in the development of both engines and refrigerators. Why was that so? Fig. 10 suggests a possible explanation. The Stirling engine's technical advantages made it a promising alternative energy-conversion technology as it may operate with a variety of energy inputs, such as biofuel, nuclear power, solar energy, and waste heat. It appears that the oil energy crisis in the 1970s and the following environmental movement in the 1980s accelerated the development of the Stirling engine. Similarly, parallel activities in the field of refrigerators were made possible due to the underlying thermodynamic principles of Stirling technology.

This finding helps us to better understand the influence of the social dimension in the Science-Technology-Society triad. The hypothesis of technology-conditioned science is a variant or manifestation of the broader *Holistic Science-Technology-Society* model. In the introductory section of this paper we indicated that in this work we would not direct much attention to the "society" domain of the triad. However, we should comment here that if it was not for the oil price surge and following intensive debates about environmental and economic issues associated with oil, we would probably not have seen the intensification of technological and scientific activities related to Stirling technology at around 1980. This result also suggests that in the example of Stirling technology, society influenced the technological domain, which later influenced scientific activities. The generalizability of this result in other technological fields may provide a productive avenue for future research. A critical implication of this result for the future is that policymaking and societal attitudes, rather than technical factors alone, may indeed play a pivotal role in the development of energy-conversion technologies.

Our results may contribute to policy measures to accelerate innovation in the quest for a transition to a low-carbon energy future. The bias of some organizations towards a conservative, structured and rationalistic scientific approach—in contrast with the uncertain trial-and-error experimentation approach of engineering-oriented technologists—needs to be revisited. It may seem counterintuitive to invest into engineering projects with imprecise *motifs* such as "We have an idea. We do not know what the result will be. We do not even know how it works. But let us first try." More broadly, it may also seem counterintuitive to support knowledge systems that "provide freedom and trust to actors to allow them to engage with complex, chaotic and uncertain issues" [168]. Nevertheless, our results have demonstrated robustly that the primary source of knowledge creation for new energy technologies is engineering activities with exploratory trial-and-error iterative experimentation, rather than scientific research. This finding has implications for the development of policies for energy technology and suggests a need for more substantial support of technological work to find innovative solutions for the energy transition. Policymakers could also significantly affect the development of low-carbon technologies by increasing incentives for the presentation of early-stage experimental works at conferences. Such earlier reports could facilitate appropriate conference "chatter" and engage scientists at earlier stages of technology development to better explain experimental results and produce general knowledge. Although our empirical findings strongly support our theory, there are nevertheless several discrepancies between expected results and actual data that deserve further investigation.

7.3. Limitations and future work

Although the evolution of patent documents and journal publications confirms our prediction for both fields—engines and refrigerators—interpreting data about the evolution of conference papers is less straightforward. Patent applications preceded conference papers after the period of conference "chatter" only in the field of Stirling engines. For Stirling refrigerators patents and conference papers kept vacillating concurrently until 2018, without any leadership of patent applications over conference papers becoming visible. This departure from our predictions evokes the need for further investigation. It is likely that this difference stems from differences in the relative maturity of the fields. The field of Stirling engines has generated almost double the number of documents as the field of Stirling refrigerators, suggesting that the interaction between patents and conference papers in the field of Stirling engines underwent a structural change with the development of Stirling technology.

As the field of Stirling engines developed, more academic scientists entered the field and started publishing conference papers; and as the proportion of academic scientists to engineers in conference papers increased, the dynamics followed the hypothesis of technology-conditioned science, under which science is led by technology. This is visible in Fig. 8-b in the way that conference papers follow patent applications. In the case of Stirling refrigerators, however, since the field is smaller in terms of absolute publication numbers, engineers still outnumbered scientists in publishing conference papers in parallel to patent applications, and in Fig. 9-b we may observe no obvious leader–follower relationship between conference papers and patents. A partial explanation for this difference between the two technological domains may be found by more closely analyzing the content of the conference papers: to what degree do they emanate from either the scientific domain or technological domain? A fruitful challenge for future research may be to investigate whether the mix of scientific and engineering inputs to the conference discussion is static or evolves as a technological field matures?

Another important topic for future research is to investigate how organizations, geographies and policy contexts affect the relationship between science and technology in a particular field. For example, were the organizations that patented and published scientific work located in the same geographic region or different regions? Do they operate in the same or different industries? How well do the publication topics in patents and journal papers correlate? How do changes in technological and scientific activity vary from country to country? Does the dynamic relationship between science and technology vary between technological fields? Investigating these matters will help us to interpret more deeply the results illustrated in Figs. 8 and 9. However, in doing so we will shift the weight of our analysis in the direction of the third domain in the S-T-S triad, namely, society. That is a subject for another paper. Importantly, our approach to understanding the genesis of low-carbon energy-conversion technologies could be nested within the responsible research and innovation epistemic community [169]. In future work, integrating the perspectives of social practices and energy justice would help to understand better the “cradle” of energy technology design.

It is also important to make several comments about our methodology for testing the generalizability of the hypothesis of technology-conditioned science. We assumed that patents represent technology and that academic papers represent science, and that both are representative units for the transfer of knowledge between the two domains. We acknowledge that this representation is not exhaustive. In future work, other vehicles or channels for the transfer of knowledge between domains should be investigated. The analysis of verbal, demonstrated or physical knowledge transfer might further refine our theoretical propositions. The assumption that there is a dynamic interplay between science and technology due to knowledge diffusion deserves further scrutiny. In addition, we analyzed only two cases of low-carbon energy technologies and we should be cautious about similar conclusions for other types of energy systems.

8. Conclusions

In this study we develop and test a hypothesis about the relationship between technology and science in the emergence of low-carbon energy-conversion technologies whereby science is conditioned by technology. In particular, we hypothesize that the timing and the degree of influence of technology and science on each other in the development of energy-conversion technologies is generally weighted more in the direction of from technology to science than from science to technology. We derived this hypothesis from historical cases of the emergence of the Stirling engine and the Stirling refrigerator—sophisticated multidisciplinary energy- conversion technologies—that developed vigorously during the second half of the Twentieth Century and early in the Twenty-First Century. We further tested and refined this hypothesis based on the results of the STS literature survey. We then tested the generalizability of the hypothesis of technology-conditioned science through statistical data analysis. Our method included examination of the evolution of publishing activities in scientific journals and patent literature, as well as conference publications, for Stirling engines and Stirling refrigerators. The empirical results confirmed the central prediction of the hypothesis: patents are published before scientific papers. These results imply a critical and defining role of experimental trial-and-error engineering activities in developing new low-carbon energy technologies and perhaps other science-intensive technologies. The results further indicate that investigation of the generalizability of our hypothesis is warranted for other types of energy-conversion technologies. The simple answer to the question we asked at the beginning of this paper is that, at least in the field of energy-conversion technology investigated here, *technology comes before science*.

The results of our research contain some important implications for future policymaking by leaders of governments, corporations and academic organizations. Most policymakers and practitioners rely too heavily on the outdated preconception that science is the precursor of new low-carbon energy-conversion technologies, or of technology more generally. Our findings, presaged by the research of others, question the validity of this commonplace presumption and provide evidence that in science-intensive fields, such as energy-conversion technology, technological activities come first, followed by scientific research with a time lag of some years. Our study thus suggests that a coordinated policymaking effort, taking in to account societal preferences, can indeed play a pivotal role in developing low-carbon energy-conversion technologies by paying more attention to the realities of the practical relationship between engineering and science in the process of technological innovation.

Given the importance of public perceptions, and the mismatch between what happens in reality and how it appears that most people (in contrast with academic experts in STS studies) think that energy technology is developed, it is imperative that we rethink the dynamics of innovation, technology and science in the energy field. If we want to overcome the tremendous societal challenge of the energy transition, policymakers and energy-related professionals need to leave aside extant commonplace presumptions by acknowledging that new knowledge and innovative solutions in the development of energy-conversion technologies tend to emanate primarily from the technological domain, with an experimental trial-and-error approach and from grappling with complex, chaotic and uncertain issues, rather than from “basic science” as such. More substantial public support should be provided for projects based on this understanding, with practical incentives being provided for experimental engineering results to be presented earlier rather than later. This would help scientists begin to understand and interpret practical experimental results earlier and to generate scientific knowledge faster, to support acceleration of technological innovation in the energy field. Changing our energy consumption and generation habits will not in itself allow us to succeed in the energy transition. Rather, we should cease naively eulogizing science—with its descriptive, rationalistic and theoretical approach—and instead place greater emphasis on encouraging the complex, chaotic and uncertain approach of experimental engineers that, at least in this study, is revealed to be *the* primary source of new knowledge in energy-conversion technologies. This does not mean that science is not important for the energy transition, but rather that it is a reactive partner with technology rather than *the* source of technological innovation in the field of low-carbon energy-conversion systems. In other words, science is conditioned by technology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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