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Article

Fostering Sustainable Energy Entrepreneurship among Students: The Business Oriented Technological System Analysis (BOTSA) Program at Eindhoven University of Technology

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Abstract: The Business Oriented Technological System Analysis (BOTSA) program is a new teaching and learning concept developed by Eindhoven University of Technology (the Netherlands) with participation from innovative companies in renewable energy. It is designed to stimulate sustainable entrepreneurship among engineering students in this field. The program combines the placement of students in companies to study and contribute to the development and incubation of sustainable energy innovations, with a curriculum at the university designed to support these internships from a scientific perspective. The teaching method assists students in developing a broad system view that enables them to analyze the potential of, and bottlenecks to promising innovations from a realistic business perspective. This empowers students to identify those techno-economic aspects that are critical to innovation success, and advise the entrepreneurs about these aspects. Experience indicates that teachers, students, and entrepreneurs find BOTSA a valuable way of coaching, learning and working. Theoretical support for this method is found in system analysis originating in evolutionary innovation theory in combination with concepts of entrepreneurship, business model generation and sustainable/green innovation.

Keywords: teaching concepts; practice-based learning; university-business collaboration; the entrepreneurial university; sustainable entrepreneurship; sustainable business; sustainable energy technologies; sustainable innovation

1. Introduction

Education and research in the field of sustainability and more specifically in the field of sustainable energy technologies has been growing in importance at universities around the world. Eindhoven University of Technology (TU/e) in the Netherlands is widely considered to be among the leading universities in Europe in this field. This paper documents how the TU/e spawned an innovative teaching and learning method aimed at fostering entrepreneurship among its students in the area of renewable energy, called "Business Oriented Technological System Analysis" (BOTSA). The program ties the university closer to dynamic business parties in a way that has value for all involved parties—teachers, entrepreneurs and students. Something that started out as a series of *ad hoc* student internships as part of an education curriculum, over time has begun to be recognized as a promising approach towards university-business collaboration-based coaching and learning with more or less formalized features, with potential to inspire others.

The main objectives of this paper are:

- to introduce the essential features of BOTSA to foster entrepreneurship among its population of students of sustainable energy technology;
- to reflect on the value and effectiveness of the approach so far; and
- to explore relevant theoretical underpinnings to deepen its academic relevance and rigour—a dimension which is still under development.

In Section 2, we explain the (practical) BOTSA method that is used to guide the students in their analysis of a technological innovation and towards the development of a business plan for this innovation. Section 3 of the paper focuses on the value and effectiveness of the BOTSA method. Section 4 discusses the ongoing process of deepening the theoretical embedding of the program. Since the approach originally developed in an organic, experiential "hands-on" manner, it was not designed with an explicit grounding in a particular scientific paradigm as such. However, in the course of time, perspectives based on innovation systems analysis by, e.g., Geels [1] began to form the backbone of the teaching and learning, supplemented by concepts and theories on entrepreneurship, business model generation and green/social innovation. Key aspects of these theoretical perspectives and their importance in providing conceptual coherence to the BOTSA methodology are explored in this section. In the concluding Section 5, key lessons learnt so far are drawn out and ideas for further development of the program are presented.

2. Key Features of BOTSA—A Method Grounded in Practice

Individual professors and research groups at the TU/e had already been working in the field of sustainable energy since the early 1970s, but the field got its first big boost in 1994 with the formal establishment of a Technology for Sustainable Development center, designed to stimulate more research and education within this field across all the university departments. The core business of this center was to build structures for financing research as well as to develop courses for different departments within this field. Over time, this work resulted also in the establishment of a new dedicated master program, Sustainable Energy Technology, in 2003. In 2010, the TU/e Board decided to focus one of the university's three strategic areas completely on energy. In 2012, a new Bachelor major programme in Sustainable Innovation was started, giving further impetus to the field. At the time of writing, more than 400 researchers are involved in this field in different faculties and research groups across the university. By being one of the full partners of the Knowledge Innovation Community InnoEnergy (KIC InnoEnergy), TU/e also demonstrated that education, research and innovation cannot remain as separate pillars in the field of energy in the modern world. It became widely felt that only a combination of education, innovation and business creation can create "world changers" who feel challenged to look for opportunities and start the energy transition towards modern sustainable energy technologies and ways to make more efficient use of energy.

Another important transition in education which coincided with the developments described above is that since 2000, the TU/e has started to stimulate educational activities to improve the entrepreneurial skills of its students. This was born of a great concern about the dismally low proportion of students starting a company after having finalized their studies, in spite of the many relations between the university and the private sector that existed even at that time. Stimulation of entrepreneurial awareness, attitudes and skills is being realized by means of additional courses, specializations and competitive challenges aimed at making students more aware of the possibility of becoming an entrepreneur after their graduation, and creating opportunities for them to work towards this objective already during their studies.

The Business Oriented Technological System Analysis (BOTSA) evolved from the confluence of the two trends sketched above. The first step that was to lead to BOTSA's establishment was a minor in "Entrepreneurship in Sustainable Energy" as part of the third year bachelor program. This was soon followed by a "Select Project of the Year" course which is part of the European Master program KIC InnoEnergy SELECT at the TU/e. The KIC InnoEnergy master SELECT is a European master program taught at several universities throughout Europe. Compared to "regular" engineering master programs in the field of sustainable energy, this program also has a strong focus on entrepreneurship, in line with the KIC InnoEnergy idea. A key feature of both the minor and the Select course is that students are challenged to make themselves familiar with a technological innovation in the field of sustainable energy, usually presented by an entrepreneur, and that they analyze this innovation in terms of its business perspective resulting in a business model, case or plan for (feasible parts of) this innovation.

At the time of starting the minor program, the teacher coaching of the student innovation analysis was relatively simple. It was guided orally in combination with a set of leading questions which were presented at the start. These questions dealt with topics which should (at least) be included in the analysis, mainly: the technological specifications, limits to the application of the technological innovation, a comparison with other technologies with similar functions, and a basic financial feasibility study.

The rationale for choosing technology as the entry point was twofold. First, the students needed to become sufficiently familiar with the innovation at hand in order to be able to advise entrepreneurs, as this should not only comprise purely business related aspects but also a forecast for their technology and the broader technological domain in which the innovation is positioned. Furthermore, for engineering students, looking at technological innovations naturally fits their capabilities and professional training background and offers them a challenging assignment. In addition, engineers in practice would also want to be intimately familiar with the technology that they are dealing with.

Students had to make unavoidable choices in the course of executing their assignment. And although technology was the prime focus, it was clear from the beginning that their choices could not be based solely on technological criteria. The sequential "pipeline" approach to technological innovation which held that innovation starts with science-driven invention, followed by technological design optimization, and finally the business plan, had become truly obsolete (see [2] for an excellent early critique of this approach). Right from the beginning, choices in the innovation trajectory would need to be made with a business perspective in mind, so the technological feasibility and efficiency would have to be analyzed in relation to existing, competitive products/processes and market conditions and trends. For example: reliability, costs, availability, legal issues (for example, intellectual property issues), and expected social impact (public acceptability of large modifications in the local environment caused by, for example, a new transport system) needed to be taken into account, right from the start. This iterative way of working by the students resulted in the strategic positioning of innovations in respect of their unique selling points (USP) and thus their business opportunities.

The features emphasized during the students' analysis in the "Project of the Year (PoY)" of the KIC InnoEnergy master SELECT program were designed in accordance with these early experiences from the minor program. The PoY is an international course simultaneously taught to the SELECT master students at three European universities: Kungliga Tekniska Högskolan (KTH, Stockholm), Universitat Politècnica de Catalunya (UPC, Barcelona) and Eindhoven University of Technology (TU/e). At the hard core of the PoY still lies the technological innovation, but the teachers prefer to emphasize a somewhat expanded version of this concept, namely the *technological system*. The students first analyze the technological innovation itself, taking into account its hardware and functioning, operation and maintenance. This is followed by the adoption of a broader systems perspective, including a study of the organization of the system and its embedding in the broader technological and economic environment in which it is expected to function. A techno-economic feasibility study and a sector study are also part of this broader system analysis. The potential market is analyzed by looking at potential users, the characteristics of the specific business sector into which the innovation will be inserted, and the economic outlook for the products/services that could be offered by the system. Finally, the scope of the analysis is expanded even further to encompass various exogenous factors of influence on this combined technological-market system, for example regulations, social behavior of groups, and the economic situation of the region, country, *etc.*, where the business based on the innovation is designed to be started and early customers are to be found.

The framework in Figure 1 below visualizes the relationship between these three different levels of analysis.

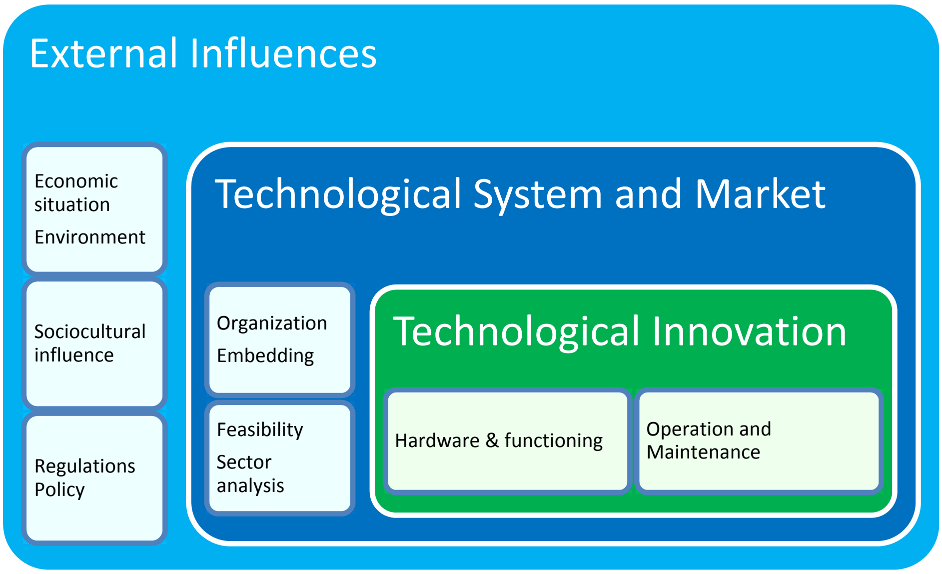

Figure 1. Visual representation of the BOTSA approach. Source: Authors.

3. The Value of the BOTSA Approach

In this section we first address the question whether the BOTSA method provides students with adequate knowledge for choosing the most promising technological innovation from a business perspective.

Teachers' experiences show that TU/e students enrolled in other programs often perform a business analysis with hardly "any" technology-specific knowledge. A good example of this is the minor "Entrepreneurship and Innovation" taught simultaneously with the minor "Entrepreneurship in Sustainable Energy", in which this black box approach to technology is practiced routinely. In contrast with the "Sustainable Energy" minor, students from that minor do not execute a technological project, but instead take several additional "entrepreneurship and innovation" related courses. However, they execute a business analysis, consisting of a feasibility study, market study, and strategy and sector analysis, just like the "Sustainable Energy" minor students. What, then, is the importance to students of conducting a separate technological system analysis of the innovation on top of this, as is done in the minor "Entrepreneurship in Sustainable Energy"?

As experience has shown, the combination of market analysis and technological system analysis allows students to obtain a thorough background giving them means to decide which (part of) the technological innovation they would like to focus on during their business analysis. Thus, the technological system analysis serves to provide more focus for the business analysis. It can also serve as a vital "reality check" concerning the question of whether preliminary promising business opportunities that are identified can really be implemented–realistically speaking. Moreover, the problems encountered through such confrontations can in turn spark new ideas and further research that lead to truly sound business opportunities—a point that will be considered further below.

Some examples from practice serve to illustrate how these interactions work. In 2010, a group of students focused on using pulsed LED light for algae growth to produce biofuels [3]. Shortly after having started their research, however, they had to conclude that using pulsed LED light did not seem to contribute to the bio productivity and therefore growth in production units, despite claims to the contrary in scientific literature [4]. Through discussion with an experienced professor at the Wageningen University and Research center (WUR), they discovered that the situation in production units was quite different from the situation in laboratories where layers of algae could be very thin and could be constituted approximately in the same position. Only in that ideal controlled environment the pulse light would be useful to enhance growth. Another issue in this same project arose from the fact that algae were also hyped during that period; this made it difficult to obtain reliable data, especially through the internet. An uncritical assessment of the available data could have easily led to the impression that algae, through conversion into biodiesel, could be a solution to many problems including the depletion of fossil fuels. The students were able to see through these inflated perspectives by conducting their own technological analysis. They managed to generate sufficient reliable information to conclude that using only the necessary part of algae (lipids) to produce bio-oil would not be feasible. Even though algae consist of 30%–60% of lipids, the price of biodiesel is low compared to production costs of algae, resulting in an infeasible business case. The students therefore decided to shift the focus of their research to produce algae through a bio-refinery concept and thereto separate them into their core elements: lipids, proteins and carbohydrates which can be used for different purposes, namely the production of food, chemical building blocks, oils and biofuels. Without a thorough technological system analysis combined with a basic financial analysis the students would not have been able to shift focus this easily. The students had become sufficiently knowledgeable on this topic to be able draw conclusions and make decisions on the most promising innovation(s) on which they therefore should focus their business case.

When we take into consideration the opinion of the students of the sustainable energy minor based on the evaluation forms that were filled in, most of them state that they obtained sufficient knowledge of “their” technological system to conduct the business analysis. We can take this also as an important indication that the method serves its intended purpose.

After the first year of teaching the minor program, it was decided to involve external clients who brought in real case assignments. Working with clients obviously would restrict the number of choices that students could make during their technological system analysis, as clients are looking for an answer to a business related question for a presented sustainable technology. An offsetting advantage is, though, that in most cases the client would also support the students during the technological analysis of their innovation, often leading to relevant information for both parties and interactive learning between them, as demonstrated in the example of the “SOWISE” boiler which is featured further on in this section.

An example in which the technical analysis did not turn out to be very useful as a precursor to the business case was the assignment provided by KIEN in 2012 [5]. KIEN is an umbrella organization consisting of and representing electromechanical installers. The objective was to contribute to the creation of a new business model for this group of installers taking into account the changing social environment in the Netherlands in which local cooperatives of proprietors/tenants are demanding energy efficiency measures in combination with installation, maintenance and repair of a locally generated energy source, like Photo Voltaic (PV) cells. The area where the action had been organized, was the district of Enspijk in the municipality of Geldermalsen. The local inhabitants of this district had been discussing their wishes several times with the municipality as well as with other organizations involved. The nature of the objective reveals that there was no technological innovation at the core of this assignment. It was attempted to make the project nevertheless meaningful from a technical point of view by requiring the students to contact electromechanical installers and consult them on technologies and related services provided, to get an understanding of the business that would be part of the model. Furthermore, combining this with considering possibilities for implementation of sustainable energy technologies in a "standard house" in this district would supposedly also lead to a useful technical analysis for the students.

This turned out to be not the case, however. From the start, the client had been in direct contact with the students, directing them immediately towards the business objective of their assignment, thereby putting the students in a difficult position. The students therefore could not rely sufficiently on their basic technical expertise and of course also noticed that their technical background was of less use to their client. Although the students did like their case study, working on their business model and working with a client, they opined that the technical component was less interesting and challenging and should have taken up less time (as acknowledged in the evaluation forms). For the supervisors this turned out to be a valuable lesson: the BOTSA method works only if assignments have a focus on a sustainable technological innovation or at least a technological component that is also organically linked with non-technical components. It can be concluded that the BOTSA method could not be used sufficiently well in this case; its distinct advantages could not be exploited. Actually this case could be an example of a project which could have been suitable for students in the minor on Entrepreneurship and Innovation, where there is no technological innovation or challenge to overcome.

A second vital question that has to be addressed in assessing BOTSA's effectiveness is whether the combination of a technological system analysis and the design of a business plan during the same project provides students with a business oriented perspective.

The underlying thinking behind BOTSA is that the students will start changing their mindset as they materialize the development of a feasible business idea during the process of analyzing their technological innovation. It can be argued that a combination of factors contributing to this change of mindset are the methodology which pushes the students towards business development, the perspective of working on a business case or plan during the second part of the project, as well as supervisors stimulating students to think like entrepreneurs. The students who participate in these projects will become engineers with affinity for entrepreneurship as they chose to specialize in this field either through a minor program or master course. This does however not mean that they already have a clear business idea or perspective, but merely that they have an open mind towards business creation and entrepreneurship and are eager to learn about this. They actually have the predisposition to become a "technological entrepreneur" [6]. The definition of this type of entrepreneurs implies a passion for technological innovation, a born curiosity for technology and the will to commercialize this, instead of solely being driven by the will to "make profit" or to make advancements in science or engineering.

One way in which the program tries to foster this mindset change is that the topic of an assignment is always described as broadly as possible, leaving the students with options to explore in different directions and make their own motivated choices based on their findings and preferences. This way of working is not something that comes naturally to engineering students, who tend to have a problem-solving mentality. If a client is involved, the assignment will be business related. To meet the objectives of their client, engineering students will tend to focus immediately on finding a business-oriented solution. Part of the exercise when applying the BOTSA method is however to not take the technological innovation for granted and stand back instead, critically assessing it from different perspectives ensuring the most important elements are covered in order to come to correct conclusions about the innovation within its (technological) system. This is essentially what the "broad systems thinking" explained in Section 2 is all about. In turn, this way of working can induce the necessity of adopting a broader perspective towards the business side of things as well.

This point is illustrated by the path followed by students researching the "SOWISE" solar boiler. The client, inventor of this boiler, had recently installed a prototype. His main question was: "How and for which segment of customers should we enter the market with the boiler in question?" The students were provided with information about the prototype and in the first instance they focused straight away on introducing this boiler into the market. However, when handing in the first version of the report of the technological system analysis, it became obvious that they had hardly compared this boiler technologically or financially to other boilers already available in the market. The students had not critically assessed the information presented by their client, and had merely tried to provide a straight answer to his question. This was reflected in their conclusion in which only advantages of the SOWISE boiler were mentioned and the main conclusion was that this boiler would contribute heavily to reaching the 20-20-20 targets of the EU. The students also made some general statements on external influences such as EU policy, rising energy prices, *etc.*, which would contribute to making the wide implementation of this boiler easier. The students were asked to reconsider their report and add data comparing the SOWISE boiler with other types of solar boilers. It became clear that although the SOWISE boiler has a number of advantages (more warm water in the morning compared to other systems, no electrical pump to circulate water), its score compared to other boilers was often average (on tank size for example). Two important disadvantages were also demonstrated; the low annual yield (3.9 GJ compared to an average of 5.5 GJ) and high costs of the system [7].

The report's conclusion after this adapted techno-economic analysis was therefore more modest and cautious, and read along the lines of "… when realizing some improvements (increased efficiency by improved insulation) the boiler could still be competitive" [7]. During the process of development of their business case, the students were even confronted with doubt whether the boiler had a USP of sufficient significance compared to available boilers. This salutary experience shows that critically analyzing the innovation from a broad perspective can contribute important insights, also to the client. In this case, the high costs compared to competitors would not have surfaced in the analysis if the students had not reconsidered different (important) technological elements. As a result, the business perspective of the students broadened as they learned to apply this system approach which gave them more insight in the real situation allowing them to assess their business case using more profound information.

On the other hand, a point that needs to be made is that in assignments when there is no external business client is involved, the assignment is generally formulated broadly allowing the students to focus on what they are good at: analyzing the functioning of the technological innovation. An important role for the supervisors in that case is to ensure that the students will not lose themselves in this. During the Project of the Year of the KIC InnoEnergy master SELECT, at some point it seemed that one of the student groups would only focus on selection of the most appropriate technology for, and technical design of a combined heat & power plant with a hydrogen-fed fuel cell. Only after several discussions with their supervisors and references to the presented method, during the final weeks of the technical part of their project they also took into account external factors, like regulations, the environment of the location where they would place their plant and they explained their possible market and presumed business model. In such cases, a well-articulated method and leading questions are important for the students to gain and keep focus, and to progress from technological system analysis to the development of a business perspective.

A final example contributes to insight whether the students obtain sufficient knowledge about the technological system to carry out their business model or plan afterwards. A group of master students executing their SELECT Project of the Year faced the challenge to analyze their technological innovation, an energy ship [8]. The concept of an energy ship revolves around the utilization of high wind speeds. A hydro turbine connected to the ship will convert the original wind power to electricity through a generator. The electricity is used to desalinate seawater and, through electrolysis, convert it to hydrogen which is one of the end products [8]. This student group took to heart the BOTSA analysis method remarkably fast and proceeded to include several methodologies for analysis which they had been recently taught in other courses at the TU/e. For instance, in order to obtain better insight in the socio-economic and cultural aspects of their innovation they used the multi-level perspective on radical innovation introduced by Geels [1]. This allowed them to systematically describe the "landscape" (*i.e.*, the exogenous context) of their innovation and explain why the transition towards a new technological regime of sustainable hydropower in which the energy ship could be one of the positive contributors—when technologically and financially proven feasible—has proven to be difficult until now. This same framework also presented them with the means to conceptualize their potential market as a niche which could contribute to a change in energy regime in shipping over time. This perspective also enabled them to reach a decision on the country where they should preferably start their business, taking into account such factors as support for niche development at policy level, energy use per capita, and shipping volume. They executed a multi-criteria analysis to evaluate the relative attractiveness of different locations on a number of criteria.

Using these different methods gave them means to structure all non-technical aspects, which obviously gave them much insight in their innovation and allowed them to take these aspects into account when executing their (basic) financial feasibility study and designing their preliminary business model. After exploration of one or more business ideas students focus on the financial analysis and relate their innovation to the sector and technological system of which it is a part. This is also part of the development of their business perspective because their idea should be tested financially. Learning about the feasibility of the business idea can be an important eye-opener to students.

Details about the different steps involved in executing the Botsa programme are provided in Box 1.

Box 1. Implementing the BOTSA method, step by step.

1. Identification of a number of "real life" business cases preferably brought in by external actors: companies who are familiar with cooperation with a students in an educational setting and with what to expect. The cases collected should contain a technological challenge and not only a business challenge. This means the cases should be focused on a "technological" product rather than on a service e.g., a heat exchanger, battery system, solar collector, or wind turbine, but not energy consultancy, or non-technological products like furniture.
2. Dependent on the number of students involved in following the course, formation of groups of 4–8 students which can choose from different topics as collected in step 1.
3. Each group then starts to study the technological aspects involved with the product involved in their selected case. They become familiar with the technological principles involved and competitive products so as to determine the technological advantage(s) of the selected product in study. They communicate their experiences with the product with company experts to verify whether they have seen things right. This phase is finalised by making a report about the findings of the product.
4. After finishing step 3, the students start to study the business case and the economic and market aspects of the product involved. The business aspects are especially supported by a business course and guidance of an experienced business person familiar with technological business. In that way, technological oriented students are optimally supported in order to familiarize themselves with business aspects of technological products in a short time. Of course, before starting the course, experienced business persons who have time to support students have to be found through the university network. Usually, they are retired people who still like to contribute to the educational system on a voluntary basis and are readily available.
5. The business experiences concerning the product are communicated with the company to verify the findings and, if necessary, to adjust them. This leads to a business report and points of advice about the business case as a whole.
6. Finally, the results are presented via oral presentations during a meeting where all the other cases and companies are also present, and preferably also some peer reviewers who have not been involved in the whole process (usually colleague teachers).

4. Theoretical Underpinnings

As the BOTSA approach gained maturity, its teachers discovered important similarities with frameworks used in innovation theories, especially the above-mentioned multi-level perspective on radical (systemic) innovations [1] and also the functions approach to "Technological Innovation Systems" developed by Hekkert *et al.* [9] and Bergek *et al.* [10]. In addition to having a well-founded theoretical constitution rooted in the paradigm of evolutionary technological change, both these frameworks offer a more practical "toolkit" to analyze and understand the complex dynamics of socio-economic changes in technological systems in a structured manner. Their usefulness in that sense is grasped quickly by students.

The multi-level perspective ("MLP") is a systems framework that is explicitly concerned with the explanation of long run transformative change in society. This is viewed in terms of transitions, which are defined as long-term, major technological changes in the way societal functions are fulfilled. These transitions involve many actors: policy makers, users, social groups, industries, research institutes, financial institutes, *etc.* As the name suggests, there are three different analytical "levels" in this framework. The middle level, which is known as the socio-technological regime, is the dominant one. It encompasses "the current dominant ways of doing things" in a particular sector and has considerable inertia resulting from well-established technologies, routines, institutions, and infrastructures. It is embedded in a contextual "landscape" of factors beyond the control of individual actors, such as climate, politics and culture. The third, niche level is the sphere from where innovations emerge, and can spread from, to dislodge, modify or transform the dominant regime. Innovations initially tend to require some degree of sheltering from regime competition to enable them to evolve to a level where they are sufficiently developed to stand on their own feet. This incubation stage involves processes of experimental learning, involving interactions between various stakeholders.

One can view the BOTSA method as involving the analysis of structures and activities of different actors at the regime and niche levels, against a contextual landscape canvas represented by the "External Influence" sphere in Figure 1. The projects that the students work on can be conceived as innovation niche experiments that are being nurtured through attention and funding from various stakeholders to enable them to evolve into concrete plans with commercial potential. Another helpful insight from the theory is the idea that sustainable innovations such as those in renewable energy involve changes in a complex, multidimensional system that is heavily dominated by fossil fuels and vested interests based on those. Changing this complex system is extremely difficult, as it encompasses radical change not only in technologies but also in the various societal dimensions that are closely interwoven with those technologies. Theoretically, BOTSA can therefore be linked easily to this theoretical framework, although it has to be said that the strength of the framework lies more in making reconstructions of historical socio-technical transitions (such as the replacement of sailing ships by steam ships) than in forward-looking analysis of possibilities for and constraints on ongoing innovations and how to best introduce these into the market–as the BOTSA method attempts to accomplish. For this reason, BOTSA also employs a range of complementary tools for harder quantitative predictive assessment, such as cost-benefit analysis and multi criteria analysis techniques.

Compared to the multi-level perspective, which revolves explicitly around the intertwining of the social and the technical spheres, there are several innovation theories that have a tighter focus on the core technological dimension of innovation, utilizing a variety of technological system concepts. There are two definitions within this research stream that fit the BOTSA method well. First, Lundvall in his writings about innovation as an interactive process [11] defined a technological innovation system (TIS) as "a combination of interrelated sectors and firms, a set of institutions, and regulations characterizing the rules of behavior and the knowledge infrastructure connected to it". Second, Bergek *et al.* [10] defined it as "the socio-technical system focused on the development, diffusion and use of a particular technology". Taken in its broader sense, BOTSA's system concept is quite similar in practice.

Although the TIS framework, like the MLP, has been primarily used for ex-post innovation analysis, its proponents have gone some way to increase its usefulness for ex ante assessment. For this purpose an analysis was introduced to measure activity within a newly emerging TIS, with the help of seven "Functions of Innovation Systems" [9,10] that a TIS must fulfill in order to stimulate the uptake and diffusion of a particular new innovation. The functions include: entrepreneurial activity, knowledge development, knowledge diffusion through networks, guidance of the search, market formation, resource mobilization and creation of legitimacy/counteracting resistance to change. Through this functions analysis, which works with measurable indicators for the performance of each function, the crucial gaps between the existing TIS and its desired performance are identified. In this way, priorities can be formulated for strategic action to address these systemic weaknesses. The framework assigns particular importance to entrepreneurs and government as driving agents in this respect. Currently, students at the TU/e are applying this method to analyze the scope for concrete innovations proposed by the (social) business sector, attempting to further increase its usefulness as a tool for ex-ante assessment.

Inherent in the need to provide students with a business perspective is imparting them with knowledge on important aspects which entrepreneurs need to take into account, as our students need to take a peek into the dynamic world of starting up a business. In his early work, Schumpeter [12] already emphasized the importance of entrepreneurs for innovation. Similarly, a strong entrepreneurial function is seen as a pivotal force for innovativeness at the systemic level in the modern technological system theories discussed above [9,10]. The BOTSA program is aimed precisely at boosting this function, through dedicated coaching and hands-on learning through practical casework.

BOTSA's approach to fostering entrepreneurship is validated by research that has found that individuals and groups can indeed be trained to develop entrepreneurial attitudes and skills, as opposed to the view that one is born with this characteristic [13]. BOTSA's learning method is based on the fact that students will be able to learn about entrepreneurship, and that their social and cultural background does not hamper their ability of being trained as an entrepreneur.

In Section 3 we already touched upon the personal character of a "technological entrepreneur". Technical entrepreneurs are found to be more "extroverted, more intuitive and more thinking-oriented than their less entrepreneurial engineering and scientific colleagues" [6]. Especially, being extroverted and thinking-orientation seem to be very fitting to the students who chose to follow the minor "Entrepreneurship in Sustainable Energy" because they need to brainstorm, discuss (new) findings, make up strategies and take decisions during the process of discovering this new manner of looking at their research topic. Additionally, we would describe these students as dynamic, open-minded and hands-on. This final characteristic can be easily recognized during the part of their project in which they need to contact experts and (competing) companies through different communication channels.

As the case studies in BOTSA have always focused on sustainable energy, it is also appropriate to look at important concepts and definitions which can be found as part of "sustainable entrepreneurship" and "sustainable innovation" for additional personality characteristics. Most applicable to BOTSA's method is the following conclusion by Schaltegger and Wagner [14]: "Sustainable entrepreneurship can be seen as dealing with a very innovative company start-up supplying environmentally and/or socially beneficial products and services with the potential to conquer a large part of the market". This captures well the characteristics of the entrepreneurs and students in the BOTSA program. They tend to be devoted to becoming entrepreneurs, but not at all costs; the result of their work needs to be a social or environmental contribution as well as a financially remunerative one.

Apart from the above theories and principles which can be considered the key cornerstones for conceptual deepening of the BOTSA method, there are several other theoretical concepts and principles that resonate closely with the way BOTSA operates in practice. Of particular relevance is the "triple helix model" [15], which looks at relations between academia, government and industry for fostering innovation. These three intervene into each other, overlap and co-shape each other's ongoing development. Especially the importance of policy influence and building strong links between academia and industry can be recognized in the BOTSA method. The triple helix literature shows that BOTSA's efforts are actually part of a broader movement underway in universities, referred to as the rise of the entrepreneurial university. As Etzkowitz remarks: "academia has become entrepreneurial in its inner dynamic as well as through external connections to business firms" [13].

BOTSA also employs a number of more practical analysis tools for preliminary business analysis. For competition analysis, recourse is often taken to the well-known sector model introduced by Michael Porter [16]. For business model development, the "Canvas" model developed by Osterwalder and Pigneur [17] provides the students with a logical manner to structure their business idea and transform it into a coherent and concrete business concept. In addition, students execute Cost-Benefit Analysis and in some cases, multi-criteria analysis or life cycle analysis.

Having said this, BOTSA can still develop much further in terms of actually integrating key principles of sustainable entrepreneurship. Considerable scope exists for inserting concepts and tools from this burgeoning literature into the programme to help the students to learn to think and act like sustainable entrepreneurs themselves. Some ideas for future development in this direction are listed here:

- Through practices and exercises, students can learn to develop a mindset and attitude that will help them to become *opportunity-focused* in their work. Opportunities for sustainable entrepreneurship generally lie in developing goods or services that meet basic human needs, empower people, bring greater convenience, and utilise idle capacity better, such as through the shared ownership or use of one piece of expensive equipment [18]. In the academic literature on sustainable entrepreneurship, it is argued that many of these opportunities arise from societal problems that spring from market failures such as environmental externalities and information assymetries. These are not addressed through 'conventional' entrepreneurial activities; in fact, they often arise from pursuing those activities. However, these problems present business potential for entrepreneurs with a more holistic view, who want to strategically combine the creation of financial and social and/or and environmental value [19].
- Students need to learn to use systematic *life-cycle thinking*. Aiming to find solutions to improve the environmental impact of a product implies the necessity of understanding the entire product lifecycle and identify the phases where there are opportunities for improvement and create and capture value, both social & environmental and economic [18]. With a life-cycle view one overcomes the compartmentalisation that is characteristic of conventional entrepreneurial approaches to innovation, which tend to create standalone solutions for one phase of a product's life cycle, while creating problems (negative externalities) for activities and actors in other

phases [19]. For example, through life-cycle thinking it becomes possible to see how waste streams occurring in one phase of a value chain can be captured and used productively for value creation in the next phase.

- Students also need to understand the *interests of all the actors* that are associated with the different phases of the life cycle, as well as the stakeholders operating in the socio-technical system that surrounds it [18]. Technical students tend to think naturally in terms of technical chains and systems, but in the BOTSA programme, they should be encouraged to think in terms of people, interests and incentives, power relations, and politics. As the examples in the previous sections have illustrated, the biggest challenge one faces in the field of sustainable innovation is generally not the development of a technology as such. Bigger challenges lie in managing the value chain and understanding and handling the differing interests of a variety of actors, some more powerful than others.
- Students will also be challenged to think about the best way to start commercialisation, and how to set out a trajectory towards the *achievement of scale* with their innovation [19]. Scale is crucial for achieving economic value for the entrepreneur as well as achieving social/ environmental impact in society. Achieving scale requires attention for the ability to manage and implement expansion in volume, and addressing issues of replicability of their innovation across different territories. However, scaling cannot be done overnight. Intelligent phasing is crucial. Different strategies are required and different priorities need to be set in the different phases of initiating and growing a new venture.
- Successful (sustainable) innovation is widely seen to result from *continuous improvement and learning*. Within BOTSA, this idea is already incorporated in the iterative manner in which the students hatch their innovative ideas and then develop their innovation in collaboration with the companies and under guidance from the teachers. This way of working could still be further formalised and perfected with principles from the ‘lean start up’ concept [20] and by emphasizing continuous interaction with the innovation’s prospective users in this process [21].
- Learning to become a sustainable entrepreneur involves, at its essence, the ability to conceive good ideas and materialise these successfully though effective thinking, decision making and action. This is a skill that can be learnt to some degree. This is where the application of basic principles from *effectuation theory* [22] could be useful for students. Effectual logic provides a way of thinking about making decisions in an uncertain environment. The aspiring entrepreneur should begin with an inventory of his/her capabilities and means, from which s/he imagines goals. The goals s/he chooses to pursue should be compatible with those capabilities and means, and failure to reach them should not lead to unmanageable disaster. The next step involves trying to enlist others to join in contributing to the new venture. Committed stakeholders will contribute ideas for further improvement of the innovation, or through financial contributions, for example. The innovation acquires traction in a larger network of actors, ultimately leading to a feasible and successful market introduction [23].
- Being a sustainable entrepreneur is also about *becoming an inspiration for others*, so that what starts with some scattered initiatives by a few pioneering individuals will grow into an innovative community that swells into a powerful social movement pushing for a large-scale

energy transition of society to renewables and high-efficiency energy applications. Students need to learn that traditional, closed business innovation strategies aimed at strong intellectual property protection are generally not conducive to achieving this kind of dynamic. Rather, what matters is working more collaboratively, sharing and inspiring each other, creating an open innovation culture [24].

5. Conclusions

The BOTSA program for technological entrepreneurship education that has evolved over time at Eindhoven University of Technology gives expression to the modern "entrepreneurial university" as its students grow more open minded towards business opportunities through the method applied in combination with supervision and skills taught through (practical) courses. They learn to apply their knowledge and skills to real business problems presented by external parties. This makes the university itself more entrepreneurial too. It is changing academia internally, and leads to better relations and understanding with external parties. This was exactly the objective of TU/e when it started with the stimulation of entrepreneurship-related education. The several successful student projects that have been carried through to date have fostered the development of new capabilities and broadened the horizons among all participating actors in sustainable energy innovation: it has cultivated a culture of technological entrepreneurship for sustainability among participating students; it has challenged its teachers to engage in business-oriented teaching and coaching, leading them to experience dynamic interactions between academic theories and real world innovation practices through close involvement with innovative private companies, and it has fostered an increased appreciation among participating entrepreneurs about how collaborating with academic partners can be of value to them in the process of developing and commercializing their innovations.

Through encouraging students to analyze promising technological innovations from a business/ market perspective, the BOTSA method helps to give focus to (technological) choices which have to be made along the way. In this manner, students become sufficiently knowledgeable on the topic at hand to be able to make sound techno-economic comparisons between competing technologies. As illustrated by the algae example, the ability to make these comparisons allows them to make choices on the direction, focus and continuation of their project during the elaboration of their business case. This can also give rise to informed advice to entrepreneurs, as demonstrated by the example of the SOWISE boiler. BOTSA provides students with the means to focus on the key issues regarding their innovation.

The development of a business mind-set in young people during their engineering education is of course the greatest value of the program. The program is attractive for students who already have the predisposition of becoming entrepreneurs or at least have an interest to understand entrepreneurship in relation to sustainable energy innovations and who are susceptible to developing a business perspective. Applying the method in combination with guidance and with courses to obtain basic entrepreneurial knowledge and skills offers such students a more complete perspective on what it means to become an innovative environmental entrepreneur. Moreover, it offers them the means and adds to their motivation and confidence to develop themselves in this direction. Examples in which the students were directed towards application of a broader systemic perspective in their analysis which turned out to be very valuable and useful, are the group that worked on the SOWISO boiler project and the group focusing on a hydrogen-fed fuel cell combined heat power plant. The broad systemic approach also allows space for students to integrate skills gained in courses taken elsewhere at the TU/e into the analysis of non-technical aspects of their innovation project, for instance by applying a multi-level perspective or functional perspective on radical innovation or carrying out a multi criteria analysis.

A start has been made in successfully underpinning the BOTSA method theoretically with evolutionary innovation theories in combination with theories on (sustainable) entrepreneurship. These theoretical concepts and approaches inform and give structure to the entire study trajectory: from the initial development of a technological system view, to the question of how to conduct a business opportunity analysis, through to the stage where the key features of the business model have been decided upon. It can therefore be concluded that this method is a good example of a combination of practice and theory that has scope for considerable cross-fertilization as practical project experiences continue to accumulate and academic reflection deepens. Achieving such cross-benefits is still ongoing work-in-progress.

BOTSA consists of development of technological entrepreneurship based on a mix of technological strength/in-depth technical expertise and development of solid business knowledge and skills. This makes it highly distinctive compared to “usual” entrepreneurial business programs that lack the technological dimension. Technical universities like the TU/e have the advantage of being uniquely positioned in this promising “innovation niche”. This offers unique education opportunities for sustainability-directed innovation, for example in co-operation with organizations like the KIC InnoEnergy and technology-driven private sector companies, from large corporations to small & medium enterprises.

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Author Contributions

Wijnker was mainly responsible for drafting Sections 1–3 and 5, while van Kasteren added to, and improved upon these texts. Romijn contributed substantially to Section 4 and undertook editorial work on the entire manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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