Feature

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Novel sustainable industrial processes: from idea to commercial scale implementation

Abstract: This article summarizes the consensus on sustainable development, shows industrial cases and provides key guidelines to transfer ideas into commercial scale processes. The triple P sustainable development concept has reached global industrial consensus and has gained importance in the making of business policies and practical implementations. Obtaining a sustainable process means then that it provides a need, is socially accepted, does no environmental harm and makes a profit. Industrial cases show that this is possible. An innovative way of obtaining sustainable solutions is by industrial symbiosis, in which very different partners such as a local government, a technology provider, a water board and a chemical company co-operate with regards to a new solution; turning a waste stream into a feed stream. Open innovation is generally a good way to obtain radical novel solutions cost-effectively. Guidelines for entering open innovation projects are provided. A technology readiness level (TRL) assessment method for process innovation with academic groups is also provided. Guidelines for effective and efficient innovation from research to commercial scale implementation, based on stage-gate innovation pathway funnel, are provided. Finally, a novel method for process concept design based on essential functions and essential inputs and outputs only, is provided.

Keywords: design; industrial; innovation; process; sustainable.

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1 Introduction

Obtaining sustainable processes that are implemented at a commercial scale is difficult for the following reasons:

1. There is a vast amount of literature on discussions about various descriptions of sustainable development.
2. Triple P sustainable development means that the process has to be embedded in its social, environmental and economic context.
3. The social context is not a static entity, but requires interaction with unusual partners.
4. The environmental context requires far lower inputs from and outputs to the environment.
5. The economic context requires that the process has lower cost than the conventional process.

This invited feature article is written to shows how all these difficulties can be overcome. It borrows considerably from three books of the author [1–3]. However, other literature is also used where needed.

It starts by summarizing the consensus on Triple P sustainable development. It then shows successful commercial scale implementations of sustainable processes, to prove that it is possible to meet all triple P goals and constraints. It also shows how process innovation with society partners, so-called social innovation, can be done successfully and that the concept of industrial symbiosis is very fruitful for this type of innovation.

Then, the advantages of open innovation are shown. Technology readiness levels (TRL) are introduced to assess academic research results for industrial use. Also, the advantages of a stage-gate innovation pathway are shown.

Finally, guidelines for process concept design in the research stage are provided to obtain radically novel solutions.

2 Sustainable development has reached consensus

Sustainable development as a specific subject started in 1987 with the Brundtland definition: “Sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are made consistent with future as well as present needs.

Sustainable development is development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs." [4].

Sustainable development is about three dimensions; social, ecological and economic. The social dimension means that developments fit in cultural institutions and people values are preserved. The ecological dimension means that the environment is not irreversibly damaged and that the precaution principle is applied, as stated in Principle 15: "In order to protect the environment, the precautionary approach shall be widely applied by states according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."[5]. The economic dimension means that developments are economical.

These dimensions were made popular by Elkington [6] by introducing the triple P catch phrase: people, planet and profit. Many companies incorporated this triple P sustainable development into their strategic goals. The World Business Counsel of Sustainable Development (WBCSD) aided in implementing the concept in business practice [7]. The United Nations World Conference in Johannesburg in 2002 adopted the triple P phrase and made it suitable for government by transforming the profit term into prosperity [8]. It is therefore concluded that triple P sustainable development has reached sufficient consensus to be fruitful for co-operations between industrial, government and academic partners.

In the book *Sustainable development in the process industries: cases and impact* [1], several successfully implemented sustainable industrial cases are described. The cases include the use of biomass for fuels [9], metal processing [10], metal scrap recycle in combination with cement and concrete production [11], food production in combination with oil refining, electricity production and cement production [11]. This illustrates that the triple P concept can also be implemented in industrial practice.

3 Industrial symbiosis and social innovation

For innovation between very different partners, including governments, industrial symbiosis is a very useful concept. It is a practical way of embedding industrial processes in society, environment and business contexts. It uses the idea waste=food, by turning waste materials and waste energy into feedstocks; hence closing material cycles. Several implemented industrial cases of industrial symbiosis, also called industrial by-product synergy, are available from Mangan [11], and Wu [12].

Wu in particular provides a spectacular case that proves the power of industrial symbiosis. It is the Dow Chemicals plant symbiosis with the city of Terneuzen, the local water board and a technology provider. It is about transforming the city waste water into boiler feed water. This symbiosis resulted in the reuse of 2.5 million m^3/year waste water for boiler feed water and an energy saving of 65%. This case won the European Responsible Care Award in 2007 [12].

The technologies applied in this industrial symbiosis case are all conventional. It is thereby a prime example of a social innovation; a new way of co-operation between industrial, governmental and institutional and technology partners where all social, ecological and economic parameters move in the desired direction.

4 Open innovation

In many cases, however, meeting triple P sustainable development goals and constraints requires radically novel technologies, which in turn require a considerable innovation effort. Open innovation with a partnership of companies and academic groups is a way of obtaining the desired result. In open innovation:

1. Best knowledge of each partner is used.
2. Risks and cost are shared.

A typical open innovation consortium for a radically novel process innovation consists of an academic group, a contract research organization, a technology provider, an engineering contractor and an end-user of the technology; a manufacturer of a chemical or other product [2].

Open innovation can also occur between partners of a value chain; so a chain of suppliers and customers to optimize a part of the value chain. This can occur, in particular, when renewable feedstocks replace fossil feedstocks. Then, novel supply chains have to be established [2].

Here is a short checklist for a manufacturer to decide whether to enter an open innovation consortium or not [3]:

1. Do you have all capabilities in your own company to bring the innovation to commercial implementation?
2. If not, can you purchase the knowledge by bilateral contracts for others?
3. If not, consider starting an open innovation consortium, or abandoning the innovation.
4. Do you foresee a potential conflict of interest now or later with a partner? Then do not pursue with that partner.

Table 1 Technology readiness level (TRL) definitions for process technologies.

TRL level	Description	Innovation stage
TRL 0	Idea stated	Discovery
TRL 1	Experimental proof of principle individual key novel process elements	Research
TRL 2	Process concept design provided	Research
TRL 3	Proof feasibility process concept design by techno-economic assessment	Research
TRL 4	Process experimentally validated by integrated mini-plant experiments	Research
TRL 5	Process techno-economics assessed by professionals in process industry	Development
TRL 6	Process technology demonstrated in industrial environment by pilot plant	Development
TRL 7	First commercial scale demonstration plant in operation	Demonstration
TRL 8	Learning points demo-plant incorporated in commercial process design	Deployment
TRL 9	Commercial process operation meeting all specifications	Deployment

5 TRL

TRL determination helps to judge a technology from outside the company, notably from universities or contract research institutes, on its readiness for commercialization. It also facilitates a discussion between the open innovation partners about the present status of the technology and what needs to be done to bring the technology to commercial implementation.

There are several descriptions of TRL. The Department of Energy of the US is the closest to the process industries [13]. The author has used this description to derive TRL level definitions that are applicable to the process industries in general and also added the stages belonging to the TRL levels. The TRL definitions and stages are provided in Table 1.

6 Innovation stage-gate funnel method

Innovation is the pathway from idea to commercial implementation. An effective and efficient method for process innovation is the 4-D stage-gate innovation funnel. The basic idea is that the most critical items for success are addressed in the early innovation stage. If the idea then fails, little money is lost.

The 4-D innovation funnel contains the stages: discovery (research), development, demonstration and deployment (commercial implementation) [2].

In the discovery (research) stage, it is important to generate novel breakthrough concepts which are much better in all three sustainable development dimensions. Green chemistry principles are of great use here [14], as well as process intensification techniques [15, 16] and functional concept design [3].

In the development stage, it is important to reduce the risks associated with direct implementation to acceptable levels at minimum cost. For process development, this means amongst others, having an integrated pilot plant down-scaled from the commercial scale design. Or in other words, first the commercial scale design is made and then the down-scaled pilot plant is designed and tested.

Demonstration plants: in general, a factor 10 smaller in capacity than full commercial scale plants, are often applied for very large processes in the oil and steel industries, to reduce the investment risk [3]. For chemical processes, the demonstration plant is also the first commercial scale plant [3].

For successful commercial scale implementation, a reliable design as well as a well-prepared start-up is essential. A practical guide from idea to commercial scale implementation is available [3].

7 Novel concept design method in research stage

To meet sustainable development goals and constraints, novel technologies will be required. These novel technologies come about via radically new concept designs. For engineers, it is a challenge to make these novel concept designs of processes, products and systems. It means designs that provide for the need of people, while having a factor 4, 10 or even 20 lower environmental impacts, are economical and socially accepted [9]. The most promising design method is described hereafter.

8 Essential functions process concept design

New design methods can help to make radically novel sustainable designs. A useful method in this respect is designing based on essential streams and essential functions. It no longer uses conventional unit operations, but instead functions [3]. By allowing only essential inputs needed for the molecular transformation function (reaction function) and only functions essential for the desired product, a minimalistic radical function design is obtained.

In essential functional process design, first the essential input and output streams are defined. This means that only output streams of value are allowed; hence, no waste streams. Also, only input streams that are absolutely necessary for the conversion are allowed; hence, no solvents or reacting agents are allowed. These requirements stem from green chemistry principles [14].

Then essential functions are identified that are needed to transform the inputs to outputs. Subsequently these essential functions are combined as much as possible into one vessel [2]. The following list of functions is helpful in identifying the essential functions:

1. Mass movement
2. Reaction
3. Heat exchange
4. Separation
5. Form change

Successful cases of this novel design method are reactive distillations for all kinds of applications [15]. In general, this method of combining essential functions generates so-called process intensification solutions [15]. These novel designs save energy, have lower diffusive emissions to the environment, lower investment cost and are much smaller in size [15, 16].

9 Interaction between design and experimental research

Process concept design also plays an important role in the research stage as a means to communicate within the research group the research items. It helps to identify lacuna in knowledge that need to be removed by experimental research. Therefore, it helps to plan the necessary experimental research and thereby speeds up the research stage and makes it more effective and efficient [3].

The concept design can also be used to carry out an economic assessment and identify risks and thereby, helps to communicate the research results with management and employees outside the research team [3].

10 Rapid triple P assessment

In concept design, a rapid assessment of the preliminary design to check on triple P criteria is necessary, so that improvements can quickly be made. To this end, rapid assessment methods on environmental, social and economic impacts have been developed: a rapid life cycle assessment, a rapid social impact assessment and a rapid economic assessment based on economic potential. All these rapid assessments are made relative to the best conventional reference case. In this relative assessment, only major improvements are taken into account. The method also includes scenarios set building to rapidly test the new concept for robustness to future uncertainties [2].

11 Conclusions

Triple P sustainable development has reached sufficient consensus for innovative co-operation between different partners.

Sustainable industrial processes have been obtained. Methods and guidelines are available for:

1. Industrial symbiosis
2. Open innovation
3. Process concept design.

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