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The Role Of Process Intensification In Cutting Greenhouse Gas Emissions

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Between 1900 and 1955 the average rate of global energy use rose from about 1 TW to 2 TW. Between 1955 and 1999 energy use rose from 2 TW to about 12 TW, and to 2006 a further 16% growth in primary energy use was recorded world-wide. There are recommendations by the UK Royal Commission on Environmental Pollution, subsequently supported by others in the UK, that we need to reduce CO_2 emissions by over 50% in order to stabilise their impact on global warming, (CO_2 being the principal gas believed to be contributing to this phenomenon). One way in which we can address this is by judicious use of process intensification technology.

Process intensification may be defined as: *"Any engineering development that leads to a substantially smaller, cleaner, safer and more energy efficient technology."* It is most often characterised by a huge reduction in plant volume – orders of magnitude – but its contribution to reducing greenhouse gas emissions may also be substantial.

Potential energy savings due to investment in process intensification were studied by a leading process *integration* company in the mid 1990s, to assist the UK Government in formulating a strategy on intensification. Overall plant intensification has been identified as having a technical potential of 40 PJ/year, (about 1 million tonnes of oil equivalent/a). The total potential energy savings due to investment in process intensification in a range of process unit operations were estimated to be over 74 PJ/y, ($1\ PJ = 10^{15} J$). Estimates for The Netherlands suggest that savings of 50-100 PJ/y should be achieved across chemicals and food processing by 2050.

This paper relates by discussion and example process intensification to the main themes of the Conference, including process integration. It also identifies the challenges that process intensification is meeting across a range of sectors of industry and commerce, in particular as they relate to greenhouse gas control. By highlighting here the main mechanisms that 'enhance' heat and mass transfer in intensified plant, the reader may be stimulated to examine his/her current inefficient processes – further pointers to assist this will be given in the verbal presentation.

1. Introduction

Process intensification offers a number of opportunities to improve energy efficiency and reduce environmental impact, see for example de Groot and van Dorst (2006) and Jachuck et al (1997). Many chemical reactions which are currently carried out as batch processes in stirred tanks, could be carried out in continuously operated, intensified reactors such as spinning disc or oscillatory baffle types. The plant used for separations can be made highly compact, while terms such as the 'pocket-sized nitric acid plant' are becoming the norm, (Perez-Ramirez and Vigeland, 2005). Here monolithic membranes have specific surface areas of 500-4000m^2/m^3 – similar to those of micro-heat exchanger-reactors that are the intensified unit operations currently receiving much attention, see Qi et al (2007)..

1.1 Process intensification - What is it?

Stankiewicz and Moulijn (2000) neatly highlighted the fact that growing world-wide competition will necessitate major changes in the ways plants are designed. The authors then produced compelling arguments to show that seven 'key themes' would guide developments underpinning these changes. These were:

- Capital investment reduction
- Energy use reduction
- Raw material cost reduction
- Increased process flexibility & inventory reduction
- Ever greater emphasis on process safety
- Increased attention to quality
- Better environmental performance

While of course not all developments will involve process intensification, it is generally acknowledged that process intensification can make a major contribution to at least six of these key themes. (It is more difficult to apply process technology to raw materials cost reduction, particularly in a world where resources are under threat and demand continues to rise due to massive growth in demand in developing economies). We can also add others:

- Size reduction for its own sake is not the be-all and end-all of PI. There are intensified processes which offer us the opportunity to create new or better products with properties which are better controlled. Pharmaceutical products which cannot be made to such a tight specification in any other way are a case in point.
- Increasing the speed of some processes can also be a strong incentive.

One of several specific definitions of process intensification (PI) sets out a selection of these themes in a different manner:

"Any chemical engineering development that leads to a substantially smaller, cleaner, safer and more energy efficient technology is process intensification!"

Stankiewicz and Moulijn missed out safety from their original statement. It has been added here because it is also an important driver in spurring business to consider PI technologies, particularly if we look at distributed manufacture. The main benefit is the dramatic reduction in hazardous inventories that can be achieved. In the words of Trevor Kletz (1998), "What you don't have can't leak".

However, within the context of this paper, it is not too difficult to see how PI can satisfy the need to reduce CO_2 emissions in a number of broad ways which derive from the key themes and the specific definition of PI above. Some of the most important benefits are listed below – no apology being made for repeating some already identified in a general context.

Reduced energy use
Reduced materials needs
Lower potential for leaks
Increased recycling capability
Reduced by-products (e.g. in reactors)/improved product purity
Compatibility with process integration methodologies

The most impressive examples of PI, when viewed from almost any vantage point, are those which reveal order of magnitude reductions in process plant size. The HiGee distillation unit of Colin Ramshaw (1983) is an early example, Fig. 1, which shows how a PI technology can reduce the visual impact of a plant, compared to a conventional design. Concepts such as the 'desk top process plant' and the 'lab on a chip' stimulate our imaginations today.

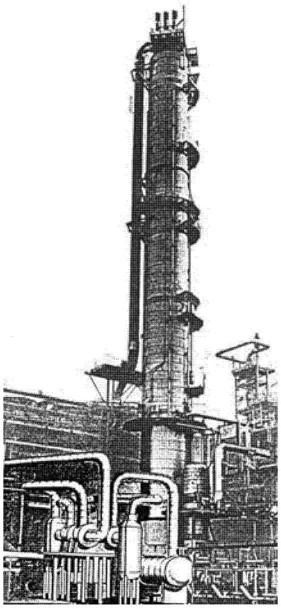

Fig. 1. Ultimate PI – the HiGee distillation unit next to its conventional counterpart

In this and other petrochemical/bulk chemical processes it has been estimated by a study co-ordinated by Senter NOVEM and Arthur D Little (2006) that energy savings of 14-25 PJ/year could be realised in Europe with PI by 2030. Adding in other sectors (fine chemicals, food etc.) the total could reach an annual 50-100 PJ by 2050.

The data in Table 1 from China on a Higee water deaeration unit of 300 t/h give some comparison of cost/performance data on an existing commercial PI unit, showing ten-fold reductions in some of the prime parameters.

Table 1. Comparison of the principal parameters of two water dearation units - one conventional and one using 'Higee' technology.

Parameter	Existing Technology	Rotating Bed Technology
Investment	1.0	0.6
Power consumption	1.0	0.8
Plant 'footprint'	1.0	0.2
Weight	1.0	0.1

1.2 Climate change

The EU has proposed that we should aim to limit temperature rise to below 2°C to avoid dangerous climate change. The IPCC conclusions suggest that this is a good working target. Earlier EU work linked a 2°C rise to atmospheric carbon dioxide at 550 ppm, and this was the assumption made for the UK Energy White Paper. But the more recent IPCC conclusions suggest that a concentration limit of about 450 ppm would be more appropriate. Defra (the UK Department of the Environment, Food & Rural Affairs) has work in hand to better define the risks associated with different carbon dioxide concentration levels.

The IPCC notes that to stabilise carbon dioxide concentrations at 450 ppm requires emissions to peak and begin to fall in the next 10-30 years. Yet emissions are unlikely to do so without concerted action. Exxon Mobil estimates that by 2020 the world will need 40% more energy than today and that 80% of that extra demand will come from developing countries.

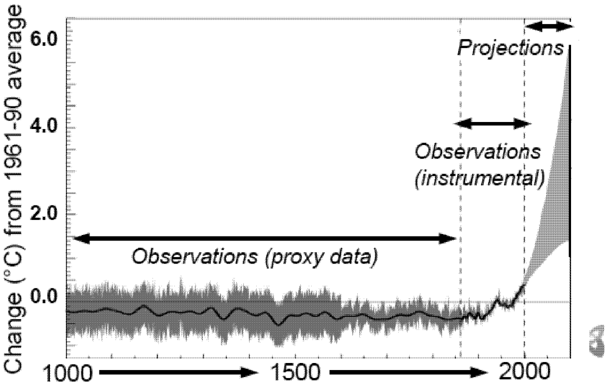

Fig. 2. Temperature changes over the last 1000 years deduced from biophysical sources such as tree rings, and projected by models over the next 100 years (IPCC) Proxy data is for Northern Hemisphere only, instrumental observations are global (see IPCC report)

Fig. 2 demonstrates the divergence between what is effectively a business-as-usual scenario and a stabilisation scenario at 550 ppm. There are recommendations by the UK Royal Commission on Environmental Pollution, subsequently supported by others in the UK, that we need to reduce CO_2 emissions by over 50% in order to stabilise their impact on global warming, (CO_2 being the principal gas believed to be contributing to this phenomenon). In the context of industry, more energy-efficient processes are those that use fewer resources in their manufacture, operation and disposal, and can produce with a minimum amount of waste – all features of energy-optimised intensified unit operations.

It is not unsurprising, therefore, that the UK Government's Energy Efficiency Best Practice Programme (EEBPP) – the first major co-ordinated action to encourage energy saving – included PI within its portfolio of energy-saving measures. We now see the US Department of Energy including PI in its portfolio, and the European Commission has reintroduced PI into its programmes, after an omission of several years.

1.3 Energy & the Environment - One of the 'Prime Movers' for PI

Between 1900 and 1955 the average rate of global energy use rose from about 1 TW to 2 TW. Between 1955 and 1999 energy use rose from 2 TW to about 12 TW, and to 2006 the use of primary energy resources grew by another 16%, ($1\ TW = 10^{12} W$).

National governments and international bodies have all proposed, and in many cases, implemented strategies for addressing greenhouse gas emissions. The UK Carbon Trust, following on from the earlier EEBPP initiative mentioned above, has categorised GHG mitigation technologies it might support into four divisions – those it will periodically review, monitor, 'consider' or focus upon. PI falls within the last category – the area which will receive greatest attention. It sits alongside combustion technology, materials, process control and separation technologies – the last two of which have particular relevance to PI.

The Carbon Trust assists companies and academia by providing funding for R & D and demonstration and judges proposals on the basis of their technological impact, as will as their potential for reducing carbon emissions. One current project (Anon, 2005) relates to the plastics and polymers sector and is directed at intensification of the thermal processes (both heating and cooling) within injection moulding – as will be shown later, heat (and mass) transfer enhancement are critical to many, if not all, PI activities.

The author, see below, has recently been involved in identifying new opportunities for Carbon Trust activities in process energy reduction. By way of brief illustration, process intensification offers a number of opportunities to improve energy efficiency and reduce environmental impact. Many chemical reactions which are currently carried out as batch processes in stirred tanks could be carried out in continuously operated, intensified reactors. This can give reductions in energy, due to, for example:

- Less unwanted byproducts - so reduced downstream processing.
- Moving from batch to continuous processing will reduce the energy need for cleaning the plant.
- More scope for process heat recovery - and higher grade heat may be available.
- Reaction rates may be speeded up, and hence there will be reduced energy losses due to shorter processing times.
- Reduced system losses

The opportunities for distributed processing should not, of course, be neglected in examination of the 'carbon footprint'.

The UK pioneered advanced compact heat exchangers such as the Printed Circuit (PCHEs) and Marbond units in the process industries, and the success of initiatives in this area – which led to the emphasis of enhancement and PI – was seen by many as the first official recognition of process intensification technologies as major tools in aiding the more efficient use of energy. This has now extended internationally and to reactors (Haugwitz et al, 2007).

2. The Technologies

2.1 Intensified heat transfer: the mechanisms involved.

Intensified heat transfer is also known as enhanced or augmented heat transfer. It forms the basis of many intensified heat exchangers, and the mechanisms used can also be applied to intensify heat transfer in other unit operations. Here, intensification involves, for example, the use of extended surfaces, or fins, to increase the heat transfer. The aim of the enhancement is to reduce the heat exchanger size and cost, without compromising performance – part of the PI philosophy.

The mechanism of intensification is a strong function of the nature of the fluid stream, (gas, liquid - in some cases a solid or mixture of all three), and the mode of heat transfer. For example, with single-phase gas streams, fins are ideal for enhancement, while in Fig. 3. the fins are combined with a two-phase 'isothermal' surface.

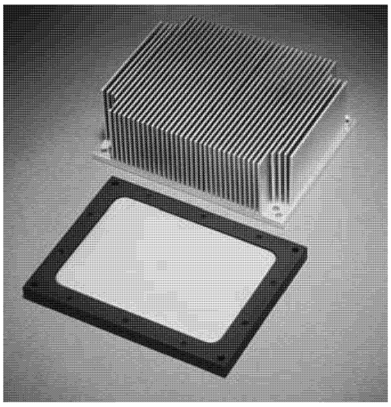

Fig. 3. Isothermalisation of a surface by two-phase heat transfer – used in lap-top computers and also in chemical reactors, (Thermacore Inc.; in Reay and Kew, 2006).

The potential of PI to influence process heat recovery is typified by the comments of Professor Ramshaw during a discussion on the UK Carbon Trust study, (Reay and Morrell, 2007) at the HEXAG meeting in Newcastle in November 2006, (Anon (a) 2007) where he suggested that catalytic plate reactors could replace much larger less efficient process reactors that use excessive quantities of heat. In some of these alternative processes the amount of recoverable waste heat would be much reduced, or even eliminated.

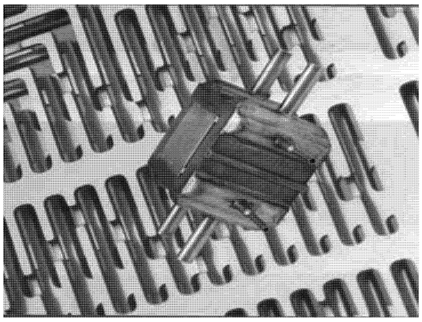

Fig. 4. The Chart Energy & Chemicals Marbond heat exchanger-reactor.

In the USA, the Department of Energy Industrial Technologies Program includes a project on micro-channel reactors – a unit developed in the UK is shown in Fig. 4 – for catalytic hydrogenation to be located at the Bristol-Meyers Squibb pharmaceuticals plant. Savings in energy are projected to be reflected in a 70% of original steam demand, 90% of electricity demand and 10% less feedstock. Some of the energy benefits arise due to a reduction in waste of 70%.

2.2 Intensified mass transfer: the mechanisms involved.

It is in the field of mass transfer that the strength of process intensification is most recognisable. It is ‘active’ mass transfer enhancement that contributes most to orders of magnitude reductions on plant size (Fig. 1). There are a number of ways of intensifying mass transfer, including:

- Rotation - in a cyclone or on a rotor
- Vibration - high frequency ultrasound, for example
- Mixing - the newer designs of in-line mixers are highly effective.

Rotation: Mass transfer can be intensified by the use of enhanced acceleration in a rotating system, either within a cyclone/vortex or a rotor – as illustrated in Fig. 5. Higher applied accelerations can produce thinner films, smaller bubbles/droplets and increase flooding velocities (for counter current systems). About two-thirds of the unit operations in process engineering involve multiple phases and may be susceptible to this intensification approach. Vortex fluidic devices and Higee rotating packed bed developments are typical examples of this technology, see for example Tai et al (2006).

Vibration: While vibration is often created in the first instance by an electric field, it is effectively a mechanical phenomenon. One of the first applications of intensive vibration forces, using a 'sonic horn' was to remove fouling from the surfaces of massive boiler heat exchangers. On a laboratory scale, the ultrasonic cleaning bath is an intensive process – now being extended to domestic washing machines by the Japanese company, Sanyo. Any surface mass transfer enhancement need would be worthy of investigation with ultrasound effects, see Moholkar and Warmoeskerken (2004). Ultrasound can be used to improve the quality of cast aluminium. The effect of ultrasound visible in Fig. 6, in this case for glass refining, is to enhance bubble removal from glass melts, allowing it to take place in minutes rather than hours. Of course it can also be used to enhance chemical reactions.

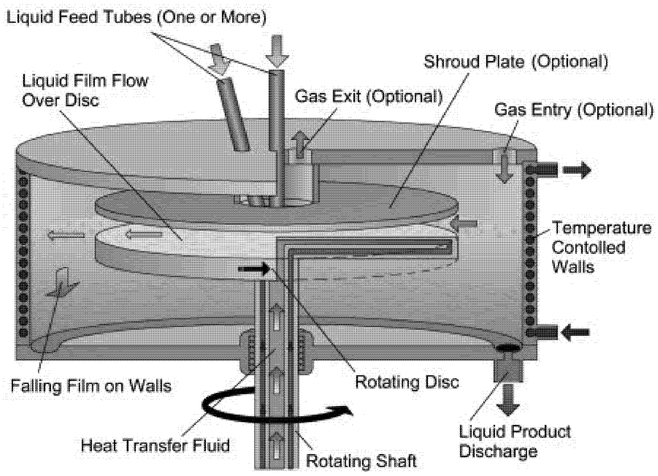

Fig. 5. The spinning disc reactor of Protensive Ltd. Active enhancement of both heat and mass transfer (Anon, 2007).

Mixing: Depending upon the viscosity of the components being mixed, the mechanisms used in mixers are similar to those for heat transfer when fluid paths are disturbed to create turbulence. The design of many types of mixers has improved in leaps and bounds recently, and mixing combined with reactions, together with 'induction-heated mixers' are of particular interest to PI engineers.

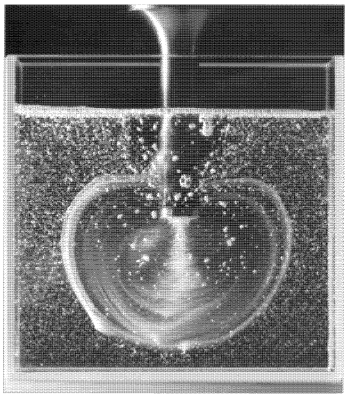

Fig. 6. Enhanced bubble removal from molten glass using ultrasound.

2.3 Electrically enhanced processes: mechanisms

Electrical enhancement has been with us for many years, and although the tranche of mechanisms involved have not been recognised by all as process intensification, most are highly effective in this role, and are under-rated in terms of the contribution they can make to PI. (Note that ultrasound may also be regarded as electrical enhancement, but is discussed separately above).

The advantages of electricity are its flexibility, ease of control, point of use delivery, and the fact that it can give better quality products and faster throughput. Electric processes allow faster, smaller, higher output per unit of energy, and lower inventory processes to be designed and operated. There are nine or more electrical processes which could be used as intensification tools. All of these are available, and several have already been used in practical applications. The more common are listed in Table 2.

Table 2. Common electric heating/enhancement methods.

Method	Frequency (where applicable)	Applications (selection)
Dielectric heating:		
Radio frequency (r.f.)	<100MHz	Plastics
Microwave	>500 MHz	Food
Induction heating		Heating metals - e.g. reactor body, paddle
Plasma heating		Calcining; producing metal spheres
Lasers	e.g infra-red, 3 x 10^{13}Hz	

The advantage of dielectric heating arises from the fact that heat is generated directly within the work material itself. Thus many of the common barriers to heat transfer by 'external' heat sources are broken down. Thus it is much more rapid than, for example, firing with hot gases, and is excellent for processing material of low thermal conductivity.

Induction heating is resistance heating, the alternating current generating electric resistance losses in the metal conductor, hence heating the workpiece. The rapid heating possible using electric fields can help to achieve catalyst light-off in combustion systems, as well as helping to sustain other catalytic reactions.

Plasma torches produce the highest industrial temperatures, locally 4000°C in the gas around the arc column. Niche applications in reactors, ceramics and metals processing exist. In future we may see use of the laser in PI - a more esoteric area, but one which modern laser technology is in sight of allowing considerable progress to be made, is that of laser reaction systems. Specifically, infra-red multiphoton dissociation (IRMPD) allows the targeting of radicals within, for example, methane. This can assist clean combustion or upgrading of the gas to higher added value chemicals.

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Two specific uses of electric fields, for heat transfer and extractions (e.g. biological) are respectively:

- Electrohydrodynamics – an enhancement method for boiling/condensation and single phase (corona wind) effects
- Electrically- enhanced extractions – charged droplets, electrostatic spraying etc, (Weatherley and Rooney, 2007).

Microwave-assisted firing, (e.g. ceramic firing assisted by microwaves) can be used to overcome temperature differentials and allows quicker firing and reduced HF emissions. This is generally twice as fast as a conventional oven, but 3-4 times in some cases. Other electric processes include magnetic bed reactors, venturi aeration, enhanced membranes and ohmic heating. In the magnetic bed reactor magnetic particles are excited in a fluid bed. This can enhance throughput of the fluidised bed, (by up to 4 in one trial) and give better yields.

The mechanisms involved in intensification may well involve an additional energy input. In most instances the extra cost of the energy input will be much less significant than the increased productivity (and other benefits) of the intensified process/plant and 'active' enhancement methods are those giving the greatest benefits.

3. PI + Process Integration

In the 1990s the then UK Energy Efficiency Office supported the development of strategies in three areas – compact heat exchangers, heat and mass transfer enhancement and process intensification (PI). There is a logic and synergy in the linking of these three strategies – compact heat exchangers are used as the basis of several intensified unit operations (e.g. heat exchanger-reactors) and, as we have seen above, enhancement is the principal mechanism behind most intensified plant (e.g. rotation, electric fields). As part of these strategies, some studies, carried out by Linnhoff March, of the energy savings were made, and data are given in Table 3.

Most of these data relate to unit operations within the chemicals and related sectors, and the technical potential for whole plant intensification, recognised as the most effective way of gaining the benefits of PI, was about 1000 ktoe/y, but it is estimated that a further 1000 kty/y would be saved if PI was extended to other process industries sectors, including glass and metals.

Table 3. Potential Energy Savings due to Investment in PI in a Range of Process Unit Operations (Chemicals Sector only).

Compact heat exchangers – 16 PJ/a
Separators – 6.2 PJ/a
Reactors – 11 PJ/a
Overall plant intensification – 40 PJ/a (technical potential)
Effluent treatment – 1 PJ/a

The above data do not take into account the increased knowledge of the potential (and actual) applications of PI since the strategies were formulated. In some instances the opportunities will have increased – in others they may have been superseded by other process improvements. An important factor is that major process changes/plant replacement would be needed to realise the savings, and a second critical observation is that integration is necessary in all except minor unit operation substitution. Effective integration can maximise emission reductions.

Interestingly, a survey on attitudes to PI (Nikoleris et al, 2002) revealed, as shown in Fig. 7, that a change to a non-carbon based economy would be a major stimulus for PI. This was borne out by other data that revealed that 60% of those surveyed felt that a switch to a hydrogen or bio-ethanol type economy would greatly benefit PI uptake. The work of Adam Harvey at Newcastle University (2006) is likely to result in a portable intensified biodiesel production unit this year. Such a trend would give a substantial stimulus to integration methodologies, which have yet, with a few exceptions, to fully incorporate the novel PI technologies emerging into the marketplace. One example is the current work on fluidised-bed reactors in the Netherlands and Germany (Deshmukh et al, 2007).

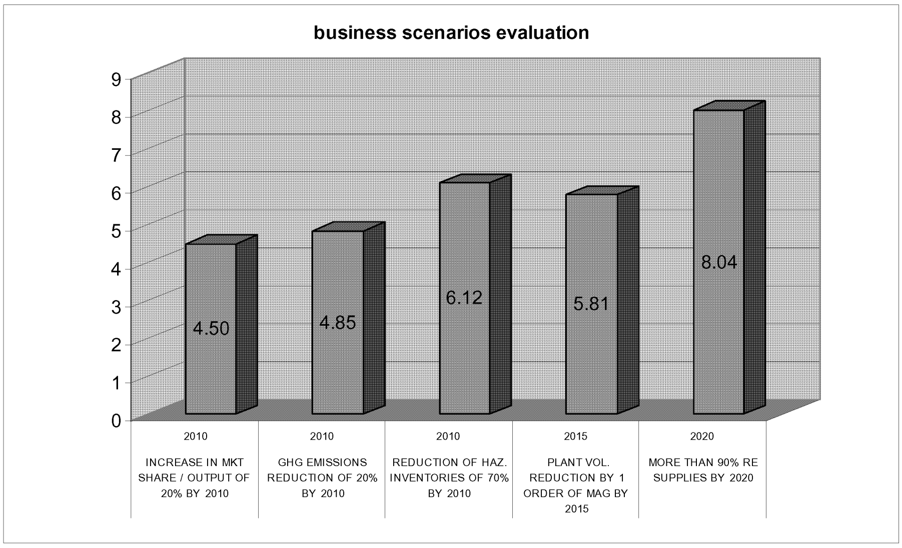

Fig. 7. PI business scenario observations.

4. Conclusions

Process Intensification, although yet to fully emerge as an established technology in the process industries, offers significant opportunities for carbon reductions in sectors ranging from chemicals to food and glass manufacture. The possibility of increased 'local' production and the growing use of biological 'renewable' feedstocks opens up new challenges and opportunities for those active in integration as well as intensification.

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