Perspective

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Opportunities for small-scale biorefinery for production of sugar and ethanol in the Netherlands

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Abstract: Developments such as the Common Agricultural Policy reform, growth of the bio-based economy, increasing energy prices, increasing sustainability demands, and expected growth of global sugar demand change the environment in which the sugar producing industry operates. In order to remain competitive and profit from this, the traditional large-scale sugar producing industry can adapt. The aim of this study was to address sustainability and energy issues of the traditional sugar production process and to provide opportunities for improving the process and value chain. The methodological approach included evaluating function and resource usage of the unit operations. More sustainable alternative unit operations and processes were identified and studied. The results indicate that the current sugar production and by-product valorization focuses on centralized processing and has been individually optimized per sector and industry based on relatively inexpensive transportation and energy without a focus as such on the bio-based economy. For incorporation of the opportunities, a process for targeting new bio-based markets and supplementing large-scale sugar production was designed. It was found that small-scale biorefineries as an alternative and/or supplementation of the traditional large-scale process have the ability to increase the overall sustainability of sugarbeet processing, for example reduce energy usage and carbon footprint, by reducing transportation movements. Moreover, it provides opportunities for leaving out certain unit operations and using less capital-intensive technologies. With a holistic approach throughout the value chain, the introduction of small-scale biorefineries can help meet the challenges of the sugar producing industry, while simultaneously benefitting people, planet, and profit. © 2014 Society of Chemical Industry and John Wiley & Sons, Ltd

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Introduction

The sugar producing industry is subject of many recent developments. These include the Common Agricultural Policy (CAP) reform, rise of the bio-based economy, increasing energy prices and increasing sustainability demands. Biorefineries offer unprecedented opportunities for biomass valorization in a bio-based economy.[1,2] The sugarbeet, with a crop yield of more than 25 ton dry weight per hectare, can become

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an important biomass source in this new economy. Ironically, in the existing value chain, sugarbeet cultivation has become less attractive. The CAP reform has led to a reduction of the guaranteed market price for sugarbeet and sugar in the European Union.[3] As a result, farmers and sugar producers have been confronted with decreasing revenues. In past decades, the evading strategy for dealing with the sugar market reform has been to focus on cost reduction by using economies of scale and operational excellence on the production of sugar. For example, about 25 years ago the Netherlands counted ten sugar production plants,[4] but since 2009 only two sugarbeet refineries have remained.[5] Due to the cost-reduction strategy, the sugar production industry is organized and optimized for centralized production of one product: white sugar. Although the energy efficiency of the sugar industry has increased considerably during the last decade,[4] cost reduction has not changed the traditional sugar beet processing being energy intensive.[6,7] In addition, energy is becoming more and more a factor of cost concern as well as of sustainability – the energy usage leaves a carbon footprint of 480 kg CO_2 per ton sugar.[4] With declining prices for sugar and increasing costs of energy, it becomes increasingly difficult to increase profit margins with the traditional production model. In addition, due to the mono-product focus, opportunities for whole crop valorization through efficient and effective use of sugarbeet are difficult to implement. Nevertheless, significant global growth in sugar demand is expected – 22% until 2021 and 50% until 2030 – and sugar quotas will be abolished by 2017,[8–10] meaning that there is opportunity for growth within the existing market and the developing bio-based economy. However, even at an average price level of €500 per ton sugar, the returns are unlikely to be sufficient for investing in additional large-scale capacity.[10] The question is therefore whether the current centralized processing model will be the most profitable to embrace this opportunity. Besides profitability, the benefits for people and planet become increasingly important to include in the strategy. Based on this outlook, we recommend a biorefinery strategy for decreasing costs and increasing revenues by efficient and effective use of sugarbeet, at optimum combined benefits for people, planet, and profit.

In this perspective, we address opportunities for improving the traditional sugar production process. These opportunities exist throughout the value chain. We show which opportunities were proposed in literature, augment these and provide alternatives. All opportunities are integrated into a new process design that allows for more sustainable but also more profitable sugarbeet cultivation.

Traditional (large-scale) process

Sugar production involves cultivation, transportation, and processing of sugarbeet and residues. Figure 1 shows a schematic overview of the standard sugar process in the Netherlands. After harvesting and transport, beets are washed and sliced into cossettes. These cossettes enter a diffusion process for sugar extraction. This extraction step yields a product called raw juice. This raw juice contains impurities, which are removed in a subsequent purification step with carbonatation lime. The juice is then concentrated by evaporation, yielding a product that is called thick juice. Finally, this thick juice is concentrated by vacuum pan boiling. Here, sucrose crystals are grown to the required size. The main product is white sugar. The by-products include tare, pellets, lime sludge, and molasses.

Several operations of the standard process are not *de facto* required for the core production process. For example, sugarbeet requires several cleaning steps to remove tare, which is also accumulated at the factory. Another example is that pellets and lime sludge, used as animal feed and soil fertilizer, respectively, are by-products that need further processing and/or transport. Furthermore, at the cost of additional energy and prior to transportation, molasses is exhausted from sugar in order to minimize sugar loss.

For many years, the sugar producing industry has optimized this process. However, it is not an optimization of the whole value chain. For one thing, additional transport of molasses to the baker's yeast and ethanol factories is required. More importantly, the costs and logistics involved with mineral recycling over the linear supply chain are significant. For example, when molasses is used for ethanol production, large amounts of vinasse are obtained. This vinasse, which is rich in salts, organic acids and minerals, is often concentrated by energy-intensive evaporation before being distributed back to the fields, which is at the cost of additional transportation movements and by itself is a logistical challenge. Although the standard sugar process is optimized for sugar production, a significant share of processing and transportation movements is thus attributed to by-products down the whole value chain. Paradoxically, the prices of by-products such as pulp and molasses have risen relative to sugar as the main product,[11] which encourages multi-product optimization and therefore redistribution of processing resources. Many of such opportunities for improvement of the standard sugar process (Fig. 1) were identified. Tables 1–3 list the opportunities for three important groups: farmer, transport, and operations, respectively, which are elaborated on in the following sections.

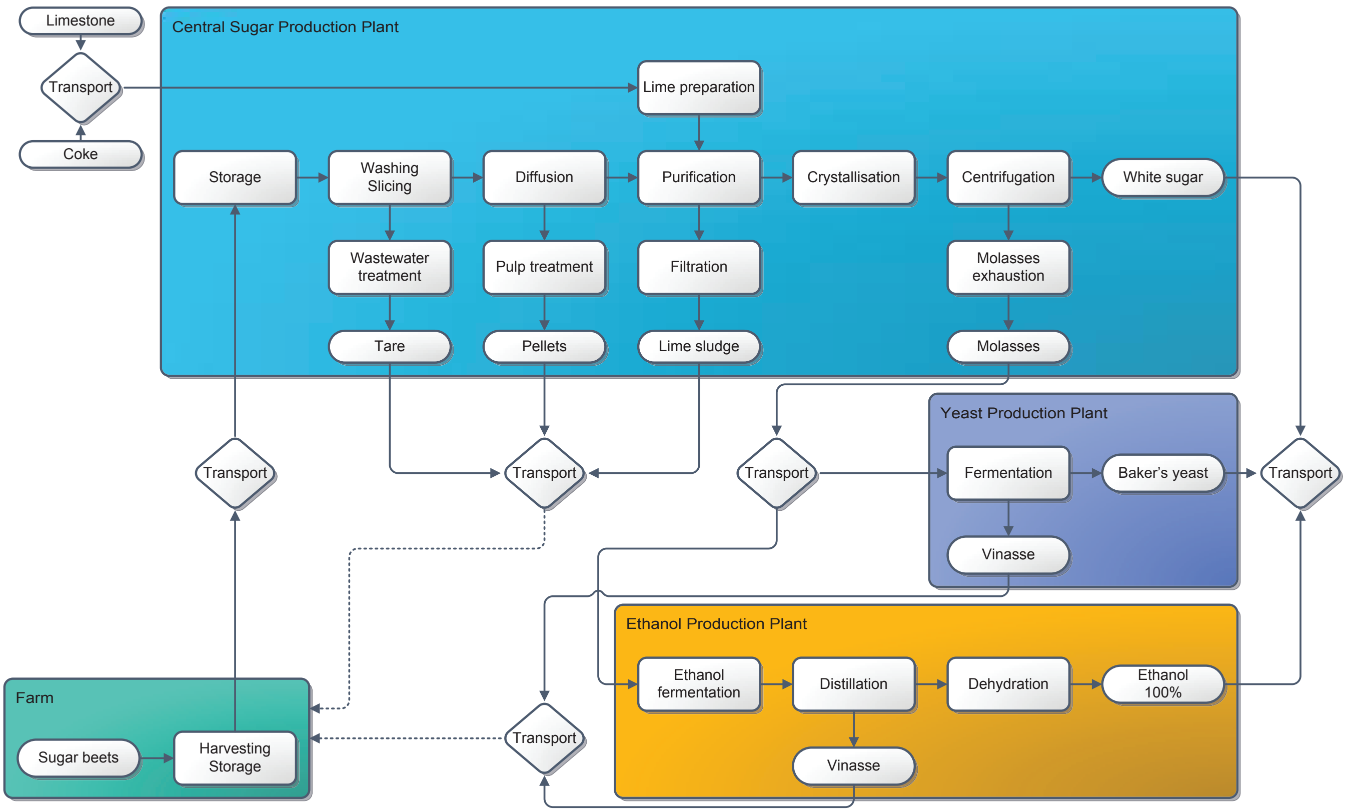

Figure 1. Block diagram of the standard sugar production process. Sugarbeet is harvested and processed in order to produce white sugar. Molasses is further used for production of baker's yeast and/or ethanol. The lines (—) indicate mass flows; the dotted lines (···) indicate optional mass flows; the colored areas indicate different production sites.

Farmer

Sugar market reform in Europe has been under debate for more than a decade. The general trend comes down to less support for farmers, which was originally introduced after World War II in order to obtain food security. The quota management, minimum guaranteed price to growers, and trade measures are all subject to change, mostly to the farmers' disadvantage. With the current value chain and mono-product focus, this will almost certainly lead to reduced income for the farmers. Since 1950, the sugar yield per hectare has more than doubled to 13.5 ton sugar per hectare in 2012.[12] However, the minimum price per ton sugarbeet for production of quota sugar has declined disproportionally from €43.12 in 2005 to €26.29 in 2010.[3] Furthermore, increased costs of fertilizers, pesticides, and energy have negative impacts on the economic outlook of farmers. Additionally, farmers are stimulated or even obliged to meet higher sustainability standards with respect to energy usage and carbon footprint. Even within corporations, as in the Netherlands, there can be friction between farmer and producer: farmers aim for the highest sugar yield per hectare whereas the producer aims for the highest sugar yield per sugarbeet.[13] In addition, the farmer is bound to a tight schedule for harvesting and cannot independently select the best moment of harvesting, while crop yield can strongly dependent on time of harvesting.[14]

In the traditional sugarbeet process, beet tops and crown are removed during harvesting (note that nowadays in the Netherlands only tops are removed) and the topped sugarbeet is transported to the central plant. There, washing and fluming takes place in order to remove tare. These early steps in the process already determine much of the farmers' perspective: the farmer sells his sugarbeet and leaves it to industry to create added value. It is a typical one-market and one-customer situation, which can create tough situations for farmers under economic pressure. Furthermore, valuable minerals, tare, and water are also removed from the arable land. Approximately two-thirds as much tare as sugar is transported and even five times more water than sugar is transported to the central processing facility.[15] The removed materials need to be replenished, commonly

Table 1. Opportunities for farmers – create more added value locally.

Type	Issue	Opportunity
Forward integration	– Farmers and sugar producers use different criteria for yield optimization. The farmer aims for the highest amount of sugar per hectare, the producer aims for highest percentage of sugar in the beet.	– Avoid the dilemma of choosing between sugar per hectare yield and sugar in beet yield by producing locally. This reduces transportation costs and can reduce evaporation costs by obtaining a higher sugar in beet yield.
	– Sugar obtains additional value after being brought by and transported to a factory for further processing. This added value is non-existing for the farmer.	– Make the farmers the producer. Create redistribution of money within the value chain.
	– Farmers get little revenues for extra production outside quotas so there is no driver for increasing production.	– Make other products, e.g. ferment sugar to ethanol. Abolish production quota (recent developments indicate that this probably will happen as of 2017).
Soil fertility	– Valuable nutrients are removed from the fields. Returning them involves processing transportation and logistical costs.	– Process sugarbeet locally so that nutrients and water do not need to be transported, isolated and/or concentrated and distributed (back) to the fields.
	– Lime sludge is transported back to the fields and releases phosphate.	– Avoid carbonatation so that the lime sludge is not produced as by-product.
Cultivation and harvesting	– Timing of harvesting is inflexible and can be unfavorable with respect to sugarbeet yield.	– Timing of harvesting according to best yield not predetermined schedule. If the beets can be harvested later, a higher yield of sugar per hectare can be obtained. Harvest and produce in an economic optimum of product yield and plant capacity.
	– Sugarbeet deteriorates slowly during storage. It needs to be protected against freezing.	– Raw material losses can be limited by short transportation lines and maximizing the farmer's economic responsibility for the raw material quality.
	– Seasonality effects limit operations of factory to harvesting months.	– Process immediately with little energy input and capital requirements to obtain stable intermediate or raw product. This can be used directly or as a precursor for central recrystallization, which can then be done year-round.

at the cost of the farmer, in order to maintain soil fertility. Recycling material from the central plant is cumbersome, and involves energy and capital-intensive processing and logistical operations to bring all material back to the land. Recent initiatives that involve partial centralized biogas fermentation do not offer improvements regarding this issue: the by-products still have associated logistical operations and costs for recycling.

Earlier work studied the position of farmers, possibilities for agricultural intensification and diversification. When considering the farmers' perspective, the ecology of scale and economy of scale should be balanced.[16] Although agricultural intensification can be obtained through crop rotation and ecological intensification, the bottleneck typically remains soil fertility, or the loss thereof.[17] When agriculture is transformed into a circular economy, many of such issues with respect to productivity can be resolved.[18–20] Product diversification by crop rotation and ethanol production can only become really sustainable if the mineral loop is closed completely.[21] However, the idea of the circular economy should be interpreted with care: central processing focused value chains still require much transportation, energy and capital for recycling of minerals and may thus yield quite unsustainable solutions.

Table 1 lists the issues with cultivation and opportunities for improving them. A sustainable solution for the mentioned issues involves two major parts. First, soil fertility should be maintained through recycling of minerals, tare, and water. While doing this, processing and logistical costs should be minimized in order to decrease the energy usage, capital requirements, and carbon footprint of sugar production. Second, farmers should be empowered through product diversification – for example, producing sugar, ethanol, electricity and recycled fertilizer – and forward integration along the value chain. In this way, farmers can create more added value and target multiple markets and customers. Successful examples of forward integration already exist today. Zvinavashe *et al*. have shown what a major impact such integration can have on cassava farmers.[22] By pre-processing cassava roots locally, a stable intermediate could be obtained and farmers gained a much stronger price negotiation position.

Transport

The Dutch sugar industry has currently two central processing plants operational. Together these plants process 5.8 million ton wet biomass per year from 73 000 ha of

Table 2. Opportunities for transport – from linear to circular.

Type	Issue	Opportunity
Farm to Factory	– Sugarbeet is transported from the field to storage clamp, via remote storage to factory storage over long distances to the central processing plant. – Reloading is cumbersome and long distance transport of whole beets including water is inefficient.	– Create biorefinery close to farming area and process to intermediate locally.
Additional raw materials	– Limestone is harvested at remote locations and needs long distance transport to sugar factory. – Coke is harvested at remote locations, transported over long distance to cokes producing factory, and transported from cokes plant to sugar factory.	– Avoid or reduce the purification step by using another method for high purity crystallization or producing a sugar with lower product purity.
Residue from sugar production	– Tare is transported away from the fields and needs storage (regulations) at factory site. After processing, tare needs new destinations. – Beet pulp is dried to create a stable intermediate in the form of pellets, which commonly undergo additional transport to animal feed. Large-scale biogas fermenters are now partially used to avoid drying, but this does not solve the complex logistics associated with recycling of minerals. – Lime sludge is transported back to the fields and contains high amounts of phosphate.	– Recycle tare locally by producing it locally. Next to avoiding transportation this extends the possibilities for re-use. Due to Dutch regulations, recycling is not allowed from a central location when the residue has left the farm. – Beet pulp still contains valuable components that can be used for the production of chemicals and fuels. After that it can be used for biogas production. – Recycle phosphate locally. Because it is soluble in water, recycling in the water fraction can be an option.
By-product	– Molasses undergo transport to either baker's yeast production facilities or to ethanol plant.	– Minimize formation of molasses and/or use directly for ethanol fermentation on-site or fermentation to other products at the same factory.
Residue from ethanol production	– Vinasse, which contains remaining minerals, is concentrated and recycled.	– Use vinasse for anaerobic fermentation to products or biogas and recycle digestate locally.
Products	– Sugar undergoes long distance transport to buyers. – Ethanol undergoes long distance transport to buyers.	– Distribute along local market. Deliver directly to sugar processing industry.

farming area.[23] Due to relatively low transportation costs, long distance transportation and centralized processing has been economically feasible. However, since 2005, crude oil prices have risen 68%.[24] As a result, transportation costs have increased disproportionally to revenues.[25] In 2009, transportation costs of sugarbeet – excluding transport and recycling costs of by-products – attributed to approximately 50% of the total processing costs,[26] which are expected to grow even further. With an average transportation distance of 90 km,[13] the total transportation costs in 2013 were about €50 million.[13] Furthermore, the growing demand for bioenergy is expected to put pressure on the capacity of agricultural supply chains.[27] As transportation costs for feedstock supply and mineral reuse represent a diseconomy of scale,[28–30] increasing transportation costs will thus make smaller-scale production that involves less transportation movements more feasible.

Much research has been done on plant size optimization by balancing transport and operating costs.[29–31] The distributed nature of biomass, high water content and large volumetric size all contribute to less favorable logistics compared to the fossil fuel counterparts. Sugarbeet, for example, contains up to 77% water.[15] The general consensus is that biomass processing has a smaller optimum plant size than fossil fuel processing, but apart from that, opinions vary. Biomass can be processed in centralized processing facilities, in distributed processing facilities, small-scale biorefineries or a combination of these. Several authors suggests splitting processes in a pre-processing and centralized processing to among other things reduce transportation volumes and limit perishability effects.[32–34] Others suggest to process biomass on smaller if not the smallest scale to obtain additional advantages with respect to investment, operational, and transport costs.[34,35] In addition, sustainability aspects, such as farmer empowerment and reducing the carbon footprint are important factors in determining processing scale.[16] Overall, new insights, developments in (bio-based) economy and changed regulations have altered the playing field of transportation and processing.

Distributed processing of sugar opposed to centralized processing can reduce the amount of transportation and

Table 3. Opportunities for processing – alternatives and cutting on unit operations.

Type	Issue	Opportunity
Operations	– Thermal treatment for extraction of sugar by diffusion uses much energy (and releases impurities into raw beet juice). – Crystallization occurs in viscous medium requiring much energy for mixing and reduces crystallization rate. – Centrifugation of viscous medium requires much electrical energy (can require up to 50% of electrical power use in factory). – Viscous massecuite and melassigenic compounds limit sugar yield.	– Use alternative extraction methods such as pulsed electric field treatment, macerating, pressing and filtration. – Use different medium and/or addition of solvents to decrease viscosity of the mixture. Obtain less sugar and direct more massecuite/molasses to fermentation (to make other products). – Accept lower yield and use massecuite as by-product or use different medium with lower viscosity. Regenerate energy (at the expense of capital). – Use different medium and/or addition of solvents to decrease viscosity of the mixture and reduce the effect of melassigenic compounds.
Purification	– Beet juice is clarified with non-renewable coke and limestone and associated mining commonly has negative ecological and environmental impacts. – Lime preparation, purification and filtration are energy intensive. – Extraction and purification often require additional chemicals (soda ash (Na_2CO_3), caustic soda (NaOH), magnesium oxide (MgO).	– Use other method for high purity crystallization or produce raw product, e.g. avoid carbonatation process. – Use different medium to decrease requirements of chemical additions.
By-products	– To reduce transport, many residues are now pretreated to reduce water content and get a stable product. Examples: beet pellets, lime sludge and vinasse. – Energy intensive three-step crystallization for molasses exhaustion. – Focus on one primary product does not allow for whole crop valorization.	– Use residues for product formation, such as ethanol and biogas. Recycle water and minerals directly to the field to avoid investment, transport and labor for handling these streams. – Use molasses after one step for producing other products to obtain more favorable energy input versus revenues ratio. – Integral economic use of all parts of a plant (including leaves), both its primary and secondary metabolites.
Capital	– High initial investment required for increasing production capacity (i.e. approximately 500 million per factory).	– Sequential construction of small-scale biorefineries in order to reduce investment risk and enable more smooth growth according to market demand.

associated costs with sugar production.[32] However, when biomass is only pre-processed in distributed facilities, long-distance transport of product intermediates and residues to central processing facilities is still required for final processing. In an ideal situation, the total transportation of all biomass such as feedstock, product intermediates, products, and by-products should be minimized throughout the whole value chain to prevent unnecessary transportation movements and logistical operations. Table 2 lists the issues of the traditional process with respect to transport and the opportunities we have identified to resolve them. Tare for example, which makes up about 11% of the sugarbeet transport weight, is unnecessarily transported to the central processing facility.[36] In addition, the water in the sugarbeet, which makes up the highest percentage of transport weight, is transported from farm to factory. The transport itself also involves several handling steps: sugarbeet is transported from the field to storage clamps, via remote storage to factory storage.[37] Using the storage clamp directly will not only reduce transportation distances but also the logistics and costs involved with reloading and storing sugarbeet along the route to the central processing plant. Besides reducing and optimizing logistics, product quality can be adjusted to requirements. For example, many industrial applications can use raw sugar instead of more costly granulated-refined (white) sugar as feedstock. Supposedly, biorefineries capable of producing raw sugar can therefore directly deliver to the sugar processing industry. This will also yield the advantage of reduced sugar distribution costs. The same holds for molasses. Although the remaining sugar in molasses before exhaustion is valuable, unexhausted molasses can also be used for ethanol production and, depending on market price and sugar to ethanol production ratio, yield a higher overall profit margin.[38]

Operations, energy, and greenhouse gas

In 2012, about 870 GWh or 3.1 PJ of thermal energy was used for sugar production,[4*] which was about 0.1% of the total energy consumption in the Netherlands.[39] Besides energy consumption, sugar production has an annual carbon footprint of 0.5 million ton CO_2: approximately 480 kg CO_2 per ton sugar.[4†] In addition, an estimate of 1.7 PJ of energy input is required for the cultivation of sugarbeet.[40‡] The energy and logistical costs for recycling minerals are at the expense and concern of the buyers of by-products.

Many studies have been conducted on the different environmental problems in sugarbeet processing. Opportunities for improvement exist in the use of new technologies, process simplifications, and by-product use. For example, pulsed electric field treatment, macerating, pressing, and filtration have been studied for the extraction of sugar from sugarbeet.[41–43] Furthermore, operations that avoid carbonatation have been proposed. These include membrane filtration,[44–46] chromatography, and cooling crystallization.[47–49] The studying of (alternative) use of by-products via life cycle assessments is also popular.[7,50–52] This includes the production of ethanol from either raw juice or molasses,[49,53,54] use of biogas and combined heat and power installations, and obtaining valuable products from vinasse.[38,51,55] Lastly, solutions have been provided for the inherent issues resulting from transportation of unwanted material, for example tare, minerals and water over large distances and, consequently, the processing and redistribution thereof.[34,35]

Analyzing the traditional sugarbeet process as depicted in Fig. 1, the most energy consuming processes are diffusion, purification, evaporation, and centrifugation. Table 3 lists the issues related to sugarbeet processing and alternatives to resolve them. Although the diffusion process has been carefully optimized in the last decade, the aim has always been to maximize sucrose yield at high purity. However, accepting a lower yield, which was heretofore considered to be unacceptable sugar loss, can reduce the capital and energy requirements considerably. The sugarbeet pulp, which in that case still contains sucrose, can be used for ethanol fermentation, thereby making use of the Pareto principle and saving resources on yield optimization. Purification could become obsolete when crystallization yields high purity crystalline sucrose from raw juice using new, better crystallization technology – optimal operation of industrial crystallization is still hampered by lack of process actuators.[56] Centrifugation is a capital intensive and an electricity consuming operation – it could take up to 50 percent of the factory's electrical power demand.[57§] The high sugar content in massecuite yields a highly viscous mixture and therefore rules out decanting or settling unit operations. The high viscosity also limits the maximum crystal content and thus yield of crystalline sucrose. Using unexhausted molasses directly for ethanol fermentation could reduce centrifugation requirements. Other options include antisolvent addition in order to obtain a less viscous medium and lower solubility of sugar, cooling crystallization for obtaining higher purity sugar, or both.[58–60] Evaporation processes can be improved as well. For example, with zeolite dehydration an energy efficiency of 75–90% can be achieved,[61] and with heat recovery the efficiency may go up to 120%.[62**] In addition, zeolite dehydration unit operations are expected to be less capital intensive, which makes the technology less scale dependent. Compared to conventional use of steam, zeolites not only offer energy saving benefits, but may also yield higher exergy efficiencies due to their tolerance for high regeneration temperatures.[63] Furthermore, process integrations can improve the sustainability of the standard process significantly.[53] These include ethanol fermentation and biogas with combined heat and power installations. For example, with respect to the costs of energy, the use of biogas installations for self-sufficient energy generation may have lower costs than purchased energy.

An integrated solution

Only a few authors have recognized the physical environment as key determining factor for sustainable processing.[64,65] Technological optimizations are indeed important and economies of scale versus transport costs should be favorable. In addition, sites for processing biomass should be strategically located.[66] Unit operations

*Excluding pulp drying and production of coke, limestone, and lime.

†Based on cradle-to-gate analysis 2008–2009, including cultivation, sugarbeet transport, and production. Current emissions are estimated at 420 opposed to 480 kg CO_2 per ton sugar due to biogas fermentation of pulp and other residues.

‡In the Netherlands this is now estimated at 14.000 MJ/ha, or 1.0 PJ.

§At the expense of additional equipment, centrifuge energy recovery can reduce this power demand.

**Energy efficiency was defined as the heat required for evaporating the amount of removed water divided by total of heat introduced to the system. The total efficiency exceeded 100% since the system used heat from the condensing vapor in regenerator exhaust air.

for recycling streams can be left out only when transport distances to biorefineries are sufficiently small.[34] Interestingly, leaving out unit operations is probably the most effective way of reducing energy input and carbon footprint of the sugar industry, which reduces specific capital and operating costs. Additional savings can be obtained by utilizing less capital intensive unit operations.[67] By incorporating the beneficial elements of small-scale production and using less capital intensive unit operations, small-scale sugarbeet biorefineries can create more cost effective and sustainable sugarbeet processing than currently available on larger scales.[2,34,68] Local processing of biomass gets rid of the dilemma of processing by-products in order to make them transportable – at the costs of capital and energy – versus transporting high volumes.

In general, small-scale biorefineries produce energy and chemicals from biomass on a scale at which combined benefits for people, planet, and profit on the (raw) products outweigh the conventional economies of scale on capital and operational expenses. The benefits of small-scale biorefining include advantages such as reduced transportation movements, reduced raw material deterioration, decreased waste treatment, increased revenues for farmers, and reduced depletion of local water and mineral resources by reuse of residual products.[16,34] Strategic advantages include the ability to quickly expand capacity, be more flexible with respect to regulations, and have shorter lead times.[69] Raw material availability as well as having multiple market outlets contributes to this. Disadvantages may include higher operational and capital expenditures as they typically have an economy of scale. Developments in information technology, advanced automation and remote control of processes can reduce the economy of scale of operational expenditure, however.[33] Sequential construction of several small-scale biorefineries could in addition reduce the economy of scale on capital expenses due to among other things multiple unit and learning economies.[70] Furthermore, as suggested in the previous section, using alternative unit operations and/or avoiding capital intensive unit operations can alleviate capital expenses.[48]

Technology for small-scale processing

Bruins and Sanders published a set of design rules for small-scale production.[34] First, determine the level of processing that is required for the product. For example, raw sugar production requires less purification. Second, make stable intermediate products to minimize the effects of seasonality with as few and low energy and capital-intensive unit operations as possible. Third, redesign the process to decrease capital investment requirements, for example by decreasing energy and exergy losses through heat exchange operations.[67] Fourth, integrate energy use and energy production by using biogas and combined heat and power generation. Last, leave on the field what is required for soil fertility. Based on these design rules and available technology, we designed a process for small-scale biorefining of sugarbeet.

Small-scale process design

The problems that were identified with the current large-scale centralized processing were analyzed for possible solutions that could be implemented in a small-scale decentralized sugarbeet factory. The right columns of Tables 1–3 show the opportunities provided for current issues in traditional sugarbeet processing. These led to the process design as provided in Fig. 2, which shows the implementation of in our opinion the most promising opportunities. This process for small-scale sugarbeet biorefinery consists of three tightly integrated sub-processes that include integration of ethanol and energy production, by-product valorization and waste stream recycling within a factory.[34,71]

The first sub-process is used for the production of raw sugar. After slicing, sucrose is extracted from the cossettes. The extraction juice is supplied to the crystallization vessel together with ethanol. Water and ethanol are stripped from the solution by passing the gaseous phase through the crystallization vessel and the water sorption zone. This sorption zone contains zeolites that can extract water from water-ethanol vapor.[72] The yielded ethanol-enriched vapor is recycled back to the crystallization vessel. Due to supersaturation of sucrose in the crystallization vessel, crystalline raw sugar is formed.[73,74] The second sub-process uses the pulp from the extraction and the bleed stream from the sugar production for fermentation of sucrose to ethanol. After fermentation, fermentation broth is supplied to a distillation column to yield ethanol. The third sub-process uses the residue from distillation, foliage, and possibly other farm residues for anaerobic fermentation to biogas. A combined heat and power generator uses this biogas to yield electricity and heat for regeneration of sorption material, crystallization and distillation. The end products of the biorefinery are raw sugar, (hydrated) ethanol, and electricity. The digestate from the biogas fermentation is recycled to the field without the need for concentrating.

Table 4. Mass balances of the traditional and the small-scale processes.[a]

	Traditional		Small-scale		
IN	Mass (ton/ha)	Sucrose (w/w)	Mass (ton/ha)	Sucrose (w/w)	References[b]
Sugarbeet	70	87	70	87	12[c]
Sugar content	12	100	12		12[c]
Tare	10		10		12[c]
Leaves	n/a		40		75
OUT	Mass (ton/ha)	Sucrose (w/w)	Mass (ton/ha)	Sucrose (w/w)	References[b]
Sugar	11.7	100	1-10	95-99	76
Ethanol	0		5-1.5		
Biogas	0		12.6[d]		
Molasses	2.7	60	0		57,76
Beet pulp (pressed)	8-35	7	0		57,76
Carbonation-lime residue	2.2	5	0		57,76

[a]Overall masses are given as wet weight and sugar content is based on total dry weight.
[b]References point to values of the traditional process.
[c]Average from 2005–2009.
[d]This corresponds to 134 GJ/ha.[77]

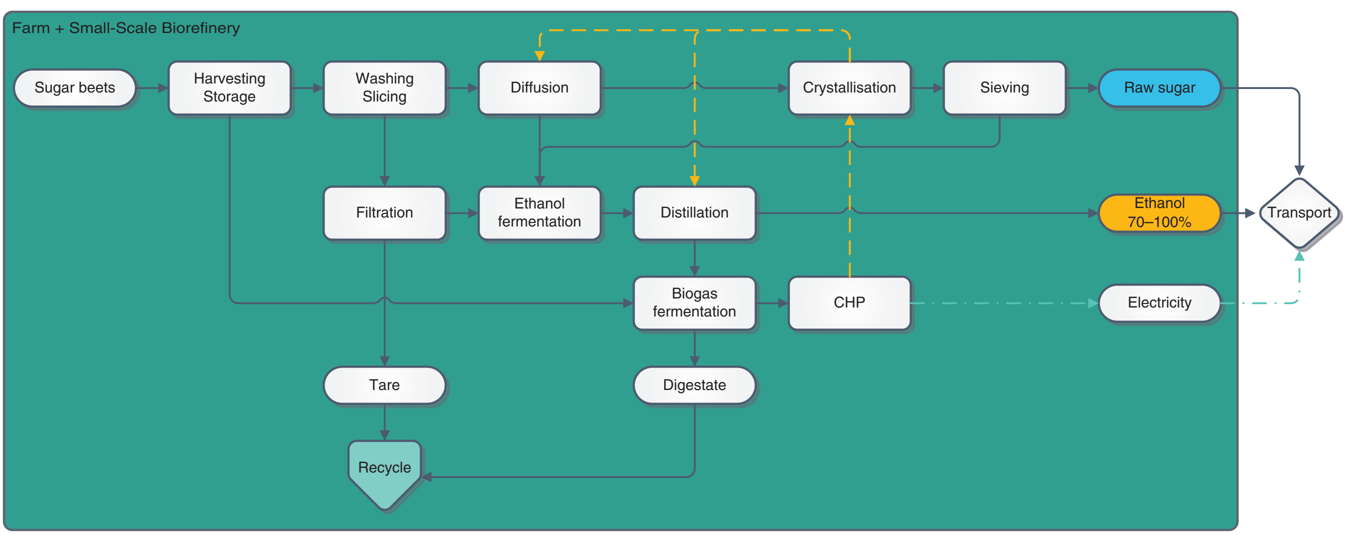

Figure 2. Block diagram of the small-scale sugarbeet biorefinery. Sugarbeet is harvested and processed in order to produce raw sugar, (hydrated) ethanol and electricity. Tare and digestate are recycled locally. The lines (—) indicate mass flows; the dotted lines (--) indicate heat transport; the dash-dot lines (-·-) indicate electricity transport; the colored area indicates the production site.

The process does not yield lime sludge, pellets, or vinasse as by-products. The mass balances of the traditional and the small-scale sugarbeet biorefinery are given in Table 4. The production ratio of sugar and ethanol can be balanced in a way that maximizes profit. Optionally, ethanol production can be left out of the process (either complete or only initially) in order to save on capital investments. Experiments have shown that with antisolvent crystallization, a sucrose purity of more than 95% could be obtained (unpublished results).

The demonstrated process in Fig. 2 solves a number of important issues as identified and described in Tables 1–3. These include empowering the farmer, maintaining soil fertility, drastically cutting down on transportation movements, making unit operations for recycling streams obsolete and enabling future growth of the sugar industry with manageable risks and investment requirements. With this process it is possible to make different products for an increasingly bio-based market. The products can target different markets and/or supplement large-scale sugar production. Conceptually, small-scale biorefining is also applicable to other industries. It is important to realize that many existing routes in the value chain have included rather than avoided the dilemmas around transportation, economy of scale and the circular economy. Therefore, we think that small-scale processing is a, if not the, route toward economically competitive sustainability in biorefinery.

Conclusion

The current value chain of sugar production and by-product valorization is based on centralized processing and is individually optimized per sector and industry during a time when transportation and energy was relatively inexpensive and the bio-based economy had no focus as such. The rising bio-based economy and changing cost structures gives ample opportunity for improving process inefficiencies related to among other things transportation and treatment of by-products. Small-scale biorefineries have the potential to alleviate costs related to transportation and processing and to increase revenues by enabling efficient and effective use of sugarbeet crops, preventing unnecessary processing and limiting transport. However, whole crop valorization on small-scale implies that biorefinery processes should be designed such that economy of scale effects are limited. In such a way, small-scale production can improve the traditional process by targeting different markets with multiple products and creating a precursor for supplementation of the standard sugar process, thereby alleviating pressure on production capacity. The introduction of the herewith-presented new technology could make small-scale the preferred choice over large-scale investments, especially when it concerns expansion of processing capacity. The farmer, environment, customer and ultimately the citizen will benefit from this redesign and redistribution of the value chain and increase the triple bottom line for People, Planet and Profit.

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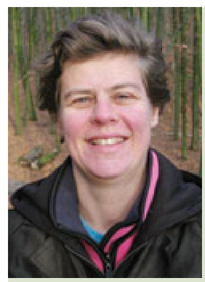

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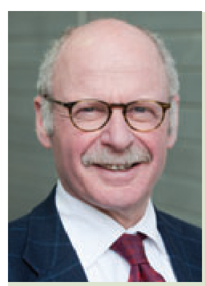

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