Published version on *Food and Bioproducts Processing*
https://doi.org/10.1016/j.fbp.2021.10.012
This version: 11/2021

Rapid repurposing of pulp and paper mills, biorefineries, and breweries for lignocellulosic sugar production in global food catastrophes

James Throup[1,†], *Juan B. García Martínez*[1,†,*], *Bryan Bals*[2], *Jacob Cates*[1,3], *Joshua M. Pearce*[4], *David C. Denkenberger*[1,3]

[1]Alliance to Feed the Earth in Disasters (ALLFED).

[2]Michigan Biotechnology Institute, 3815 Technology Boulevard, Lansing, MI, USA 48910

[3]University of Alaska Fairbanks (Mechanical Engineering and Alaska Center for Energy and Power), Fairbanks, AK, USA 99775

[4]John M. Thompson Centre for Engineering Leadership and Innovation, Western University, London, ON, Canada N6A 5B9

*Corresponding author. Contact at: juan@allfed.info

† J. Throup and J. B. García Martínez contributed equally to this work

Abstract

Producing sugar from lignocellulosic biomass is a promising resilient food solution to counter the near-total global failure of food production due to the agricultural collapse that would likely follow an abrupt sunlight reduction catastrophe such as a nuclear winter, a supervolcanic eruption, or a large asteroid or comet impact.

This study examines how quickly edible sugar production could be ramped up globally by repurposing pulp and paper mills, sugarcane biorefineries, corn biorefineries, and breweries for lignocellulosic sugar production. A sub-unit component comparison to the NREL 2017 Biochemical Sugar Model indicates that 85%, 61%, 62%, and 38% of ISBL unit components are present, respectively. Fast construction methods were studied to analyze how this and other industrial foods could be rapidly leveraged in a catastrophe.

Results suggest that the world's current sugar demand could quickly be fulfilled by repurposing pulp and paper mills for lignocellulosic sugar production, given 5 months of production ramp-up and 24/7 construction. This method could reduce construction time to an estimated 32% of the original at an increased labor cost of 1.47 times, resulting in sugar production beginning 5 months after the catastrophe at a retail cost of $0.82 USD/kg. This could not only contribute a significant share of the food requirement after the catastrophe (~28% within the first year), but also be key to preventing global starvation between the time at which global food storages run dry and other resilient food solutions can scale up significantly.

This study aims to serve as the basis for more comprehensive scenario analyses. More research is needed to characterize material and labor constraints to fast response in more depth; repurposing and fast construction pilot studies and food safety studies are recommended.

Keywords

Repurposing of factories; Sugar from lignocellulosic biomass; Resilient food; Food security; Global catastrophic risk; Existential risk

Highlights

- Existing infrastructure was assessed for repurposing to lignocellulosic sugar production.
- Pulp & paper factories showed 85% component match with the NSM reference plant.
- Lignocellulosic sugar could fulfill global sugar demand in 5 months after catastrophe strikes.
- The cost of sugar produced this way is estimated at $0.82/kg in the nuclear winter scenario.
- Factory construction time can be reduced to 32% for a 1.47 times increase in labor cost.

Abbreviations

Capital expenditure (CAPEX)

Chemical Engineering Plant Cost Index (CEPCI)

Global catastrophic risk (GCR)

Inside battery limits (ISBL)

Million liters per year (MLPY)

Million gallons per year (MGPY)

National Renewable Energy Laboratory (NREL)

Net present value (NPV)

NREL 2017 Biochemical Sugar Model (NSM)

Pulp and paper mill (PPM)

Total capital investment (TCI)

Total direct costs (TDC)

1 Introduction

The COVID-19 pandemic has laid bare the vulnerabilities of the food system to global effects, with the cascading impacts of both the spread of the virus and the measures put in place to contain it causing difficulties across society. Examples of these difficulties include increased hunger among workers that are paid daily and depend on these daily wages for food, and disruptions in supply chains caused by workers that are ill or otherwise unable to work due to the pandemic (Terp et al., 2020). The world's climate is changing and this will alter not only the long-term average temperature, precipitation rates, and other parameters, but also their variability (Bailey et al., 2015). This changing climate landscape is expected to make more severe shocks to the food system more likely (Latimer and Zuckerberg, 2019). The increasing likelihood of severe weather events around the globe makes it increasingly likely that the breadbaskets—those regions that provide the majority of our staple grains—will experience coincident shocks. This scenario could result in a multiple breadbasket failure that would cause global increases in the price of food, forcing more people into starvation (Bailey et al., 2015; Janetos et al., 2017). These breadbasket regions have been identified by (Gaupp et al., 2020), mainly including parts of the United States, Brazil, Central Europe, Eastern Europe, China, India, Indonesia, and South Australia. For wheat, maize, soybean, and rice, these breadbasket regions respectively account for 56%, 56%, 73%, and 38% of the total global production in 2012, while accounting for a comparatively small fraction of the Earth's surface. There are several other risks to global agriculture, including superweeds, crop pathogens, super crop pests, super bacteria, abrupt climate change, slow climate change that is extreme (>5 °C), or pollinator loss (Denkenberger and Pearce, 2015; Pearce et al., 2019).

This raises the question of how much worse a shock to global food production could be. The likely worst-case shock to global food production would occur if the sun's light became abruptly reduced. There are several global catastrophes that could abruptly reduce the amount of sunlight reaching the surface of the Earth, preventing traditional agriculture from fulfilling its role of feeding everyone. These include the eruption of a supervolcano, a large asteroid or comet strike, or a nuclear war (Denkenberger and Pearce, 2015). Nuclear war has been quantitatively estimated to have a chance of ~1% per annum (Barrett et al., 2013; Hellman, 2008), making it the most probable of these three scenarios given an estimated chance per century of ~0.01% for a large asteroid or comet impact and ~0.1% for a supervolcanic eruption (Denkenberger and Pearce, 2014). While nuclear weapon stockpiles have fallen since the height of the Cold War, 8 of the 9 nuclear powers are upgrading and modernizing their weapons, each holding more than the "national pragmatic safety limit" of 100, which is the limit in which using more nuclear weapons even in the best-case scenario is counter to the national interest, due to the expected environmental blowback (Denkenberger and Pearce, 2018a).

A nuclear war would threaten the lives of billions of people in the resulting nuclear winter, dwarfing the hundreds of millions who would be affected as a direct result of the strikes (Coupe et al., 2019). It is expected that the cooling effects would cause the climate to disrupt agriculture for ~6 years, with the resulting famine's death toll estimated to be in the billions (Robock et al., 2007). This global catastrophic risk (GCR) could potentially lead to the collapse of civilization, and if recovery did not occur, to a long-term reduction in humanity's potential, which is one definition of existential risk (Bostrom, 2013). Stored food is frequently suggested as a method for increasing resilience against global food catastrophes, however stockpiling food increases the cost of food in the present, which aggravates current global hunger (Baum et al., 2015). In addition, given the expected length of a nuclear winter, the total cost would be exorbitant (Denkenberger and Pearce, 2014). Current global food stockpiles are expected to last 4–6 months, producing a need to scale at speed (Baum et al., 2015).

A common denominator in any of these scenarios is that a key input to agriculture has been affected, causing global food shortages. Humanity can build resilience or respond to these scenarios by turning to resilient alternative foods for sunlight reduction GCRs: those produced from energy sources other than the sun to produce humanity's 1.7 billion tonnes carbohydrate equivalent calorific food consumption requirement. Fossil fuels, CO_2 and bioresources such as biomass have been suggested as clear candidates to create resilient foods, given their abundance. A previous study has shown, with an order-of-magnitude technical assessment, that it is possible to use these resources to create enough food to feed the world's population in the event that the sunlight reduction becomes significant for 5 years (Denkenberger and Pearce, 2015). It would be technically feasible to produce enough calories to fulfill global human caloric requirements. Initial estimates also show that it could be possible to provide a nutritionally balanced diet to maintain a reasonable level of health (Denkenberger and Pearce, 2018b).

These resilient food solutions included scale-up of global seaweed production (Mill et al., to be published), single cell proteins, leaf protein concentrate (Pearce et al., 2019), sardines, mushroom or bacteria growth on biomass, ruminants, and lignocellulosic sugar production (Denkenberger and Pearce, 2014). The simpler analysis performed in this previous work estimated that cellulosic sugar could scale to reach 100% of global human caloric requirements after a year (Denkenberger and Pearce, 2014), which has turned out to be optimistic. More detailed analysis has been conducted investigating other industrial solutions such as single cell protein from natural gas (García Martínez et al., 2020) or from CO_2 and hydrogen (García Martínez et al., 2021d), synthetic fat (García Martínez et al., 2021b), and acetic acid from CO_2 via microbial electrosynthesis (García Martínez et al., 2021c). CO_2 could also be used to chemically synthesize carbohydrates (García Martínez et al., 2021a). Scaling greenhouses to grow fresh produce in the tropics was estimated to potentially be capable of producing over a third of the world's calories a year after the catastrophe (Alvarado et al., 2020). Cool tolerant crops could be relocated to new areas with climates adequate for cultivation. Seaweed is expected to ramp up fast, potentially being able to meet the equivalent of the minimum global human caloric requirements after 6 months. Initial screening for toxins in leaves found the red maple leaf to contain at least 8 toxic chemicals, but nonetheless leaf concentrate could be consumed in small quantities for micronutrients (Pearce et al., 2019). Building resilience in the food system is critical alongside continuity of supply (Seekell et al., 2017), but unless food is already being largely produced from bioresources, there is likely to be a large discontinuity in production globally during the gap between stored food running out (4–6 months after the catastrophe) and the highlighted resilient foods beginning production (Baum et al., 2015).

The key question for any resilient food source in a food GCR scenario is therefore: How quickly can humanity ramp up resilient food production to feed as many of those going hungry as possible, at a cost low enough to be affordable?

The previous analysis (Denkenberger and Pearce, 2014) suggested significant potential for converting lignocellulosic biomass into sugar for fast and inexpensive food production. The objective of this work is therefore to study in more depth how quickly lignocellulosic sugar production could be ramped up in extreme food shortages, and to investigate means of speeding up the time to production. The study also investigated repurposing other industries to produce sugar from lignocellulose and how quickly this could be done, including the cost of sugar produced by these methods. This food source could contribute to increasing diet diversity and redundancy in food production during the catastrophe. It is important to have an array of resilient food production methods as wide as possible in case some of these turn out to be inappropriate for a given catastrophe scenario or regional context. As a low cost and fast-scaling resilient food, lignocellulosic sugar could serve as a caloric supplement to prevent starvation among the poorest populations. In addition, sugar can also be used as a feedstock for production of other nutritionally useful products, such as vitamins produced via biochemical processing (El-Mansi et al., 2018) or mycoprotein (Souza Filho et al., 2019). The process could also potentially be combined with leaf protein concentrate production when using certain types of leafy biomass as a feedstock (Fist et al., 2021) to simultaneously obtain a more nutritionally rich product. Ultimately, this study aims to serve as part of the foundation for more comprehensive scenario analyses.

Lignocellulosic sugar production is a process that takes in woody or leafy biomass, for example agricultural residues such as sugarcane bagasse, corn stover, wheat or rice straw, or switchgrass and produces sugars from them. Lignocellulosic biomass comprises cellulose, hemicellulose, and lignin, in varying quantities depending on the feedstock source, with typical amounts of 40–50% cellulose, 25–30% hemicellulose, and 15–20% lignin (Grotewold et al., 2015). The majority of the work on lignocellulosic sugar production thus far has been focused on using it as an intermediate step towards ethanol production; a 2016 request for information from the US Department of Energy received 21 responses from lignocellulosic sugar companies or institutions (U.S. DOE, 2016), 11 of which were capable of producing sugar at the scale of tonnes per day. Only one mentioned that the sugar it was producing was an edible product: the American Science and Technology Corporation. Since then, Renmatix has become the industry leader in the development of edible cellulosic sugars, with its patented supercritical hydrolysis technology enabling edible sugar production (Kazachkin et al., 2015). Comet Bio, a competitor, has developed an enzymatic activation process that produces edible sugars. Each of these technologies achieves yields of up to 85% and 90% of the theoretical yield, respectively (Richard and D'agostino, 2016).

The final sugar product must be safe to eat as human food, thus virtually free of toxins. Furfural is a toxic chemical that can be produced as a byproduct of the pretreatment process, which could be dealt with via a separation scheme such as proposed by (Moncada et al., 2018). It is safe to eat the hemicellulose and lignin obtained concurrently with the sugar in the process of breaking down the lignocellulosic biomass, as these typically are major components of dietary fiber. However, the large majority of them should ideally be absent from the final sugar product. Food safety studies of the final sugar product ought to be performed to address these and other safety issues prior to its proposed use as emergency food.

Repurposing industrial facilities into lignocellulosic biorefineries has been considered before, and the facilities that have been considered include pulp and paper mills and first-generation biorefineries (Rein, 2007; Huang et al., 2010; Gonzalez et al., 2011; Fornell, 2012; Phillips et al., 2013; Martinkus and Wolcott, 2017; Branco et al., 2019). Studies on repurposing facilities for the production of edible lignocellulosic sugar have not been found in the literature.

2 Materials and methods

2.1 Methodology overview

This section details the lignocellulosic sugar facility model that the study was based around and the methods that were employed in the calculations to achieve the results. Options for reducing the construction time of facilities from the literature are compared. The method used to find the cost of repurposing industries with similar components into lignocellulosic sugar production plants is detailed. The study considers four industrial facilities for retrofitting: sugarcane biorefineries, corn biorefineries, pulp and paper mills (PPM), and breweries. The key assumptions used are also outlined and the weaknesses of the study highlighted.

As mentioned in Section 1, the two metrics that characterize the potential of lignocellulosic sugar as a resilient food for GCRs are: how fast the sugar production can be ramped up to counter agricultural losses as soon as possible, and how inexpensive the sugar production cost is, so that the largest number of people could afford it. Figure 1 summarizes the methodology described in Sections 2 and 3, showing how these results are estimated from the starting points of the calculation.

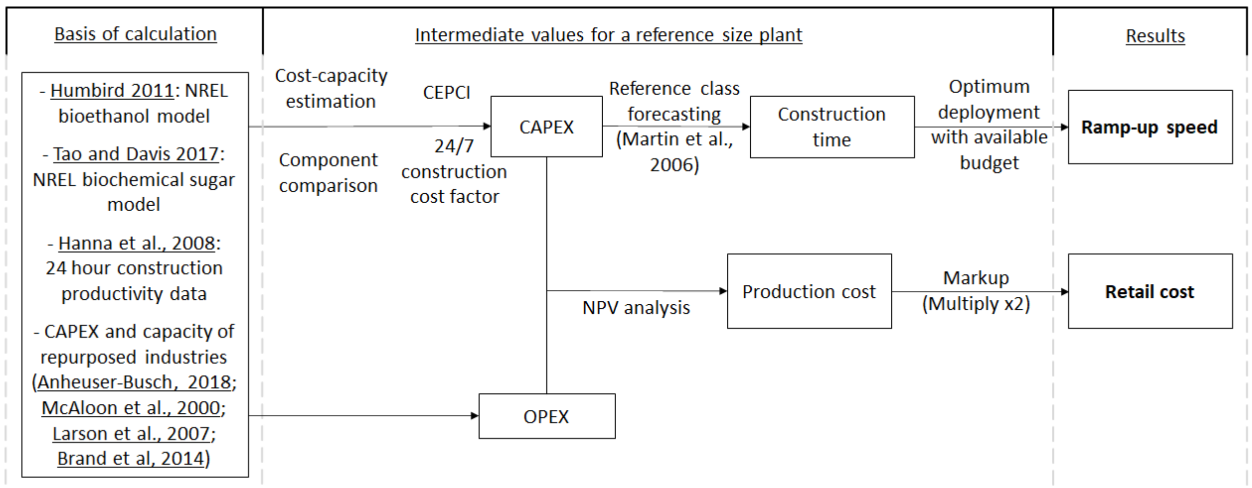

Figure 1. Methodology flowchart (CAPEX: capital expenditure, OPEX: operational expenditure, NPV: net present value, CEPCI: Chemical Engineering Plant Cost Index).

2.2 Reference plant: NREL 2017 Biochemical Sugar Model (NSM)

Ideally the model for the lignocellulosic sugar facility would be based on commercially proven lignocellulosic sugar production processes, such as that employed by Comet Bio or Renmatix (Kazachkin et al., 2015; Richard and D'agostino, 2016). However, as facility and component costings are commercially sensitive, a representative model was used from the literature.

The National Renewable Energy Laboratory (NREL) in the US developed a detailed report on the production of ethanol from lignocellulose (Humbird et al., 2011), including a model, the NREL 2017 Biochemical Sugar Model (NSM), that costed this process at the sugar stream produced after hydrolysis (Tao and Davis, 2017). NREL stresses that the sugars produced as part of the model are "imaginary"; however, the two-step enzymatic treatment process is similar to that employed by Comet Bio and was therefore used here as a representative reference plant for new builds and to compare the components of other industries for repurposing.

The NSM suggests a production rate of 47 tonne/h (dry) of sugars for a facility costing $468 million (Total Capital Investment in 2014 USD). All sugars expected to be part of the final product stream are edible, but arabinose is non-digestible (does not contribute to the nutritional content) and xylose is partially digestible, with a contribution of 2.4 kcal/g (PubChem, 2021), lower than the average Atwater factor of 4 kcal/g for carbohydrates (Merrill and Watt, 1955). Based on the composition given by the NSM and these values we estimate a calorie content of 3.3 kcal/g for the dry sugar mixture product, or analogously a sugar production rate of 39 tonne/h of carbohydrate equivalent (4 kcal/g) for the proposed NSM reference plant product stream. However, the actual proportion of digestible sugars obtained will vary depending on the proportion of cellulose in the feedstock used.

2.3 Repurposing similar industries: component comparison

Repurposing industrial facilities was considered as another method for creating food production plants. This has the benefit of some of the required components already existing onsite and not needing to develop the site or build ancillary buildings, such as warehouses. An initial scoping of different markets and industries was undertaken to establish which were the most promising for repurposing. Industries that did not involve chemical manufacturing processes were removed, along with those that would not contain relevant components. Process flow diagrams for each industry were found and compared to the reference plants' component listings to assess which industry would be the most suitable for repurposing. The industries included were pulp and paper, corn to ethanol, sugarcane to ethanol, and brewing. Other industries for future work include distilleries, biodiesel, and second-generation biorefineries producing ethanol from lignocellulose. Second-generation biorefineries were investigated, and although they show a good match in components for repurposing, they were not promising at a global scale, given how few of these plants exist compared to corn and sugarcane biorefineries. The total installed capacity of second-generation biofuels globally is estimated around 1,400 million liters in 2020, compared to nearly two orders of magnitude larger production from first generation facilities (Susmozas et al., 2020). Actual installed capacity markedly lags behind the projected volume of 40,000 million liters for 2020 (USDA, 2012). The biodiesel industry was left for future work.

Martinkus and Wolcott's framework for quantitatively assessing the repurposing potential of biorefineries is based on the assumption that the economic valuation of infrastructure and assets present in a biorefinery can be used to estimate the repurpose costs of the facility (Martinkus and Wolcott, 2017). This assumption is employed in this study. The method employed here followed Martinkus and Wolcott's method in comparing the inside battery limit costs (ISBL) of each unit operation of the NSM and the reference plants of the industries to be repurposed to find a percentage of components present. This was achieved by determining an equivalent size of a sugar plant by comparing both the reaction time and biomass concentration in the existing industry to the expected values in a sugar plant.

Martinkus and Wolcott's method includes the use of aerial imagery for assessing a site's facilities such as buildings and sidewalks. This was deemed out of scope for this study, as each individual site was not being proposed for repurposing and thus the rest of the direct and indirect costs were calculated in line with the NSM's costing assumptions, for example additional piping work assumed to be 4.5% of ISBL costs. Martinkus and Wolcott conclude that the facility with the greatest capital cost savings is theoretically the least costly to repurpose, providing lower risk to investors. Prior to applying these proportionate costs of the ISBL, the ISBL costs were scaled to factor in two changes. The first change involved scaling the plant to the theoretical average-sized plant by considering the output of each industry and total number of facilities worldwide, as discussed in Section 3.2. The second was the increase in cost of using the 24/7 construction method for fast construction as discussed in Section 3.6.1.

2.4 Assumptions

The study uses an nth-plant assumption: that the costs to build or repurpose are as reflected in the component comparison table, and that when these technologies are implemented, they do not require any research and development to function. The start-up time is therefore limited to a quarter of the length of the initial expected build time prior to any fast construction methods being employed. Operating costs were assumed equivalent to scaling the NSM's operating costs to the size of the facility being considered. Food production standards are different to those used in industrial biotechnology, requiring complete disassembly for cleaning (Warner, 2019). It was assumed that during such a severe catastrophe these standards would be relaxed, but further work is needed to ascertain if this would be the case, as well as for scenarios that would be less severe.

This study considers a worst case agricultural shortfall: a full-scale nuclear war between NATO and Russia that creates a nuclear winter as described by the 150 Tg case by (Robock et al., 2007); results for lesser shortfalls can be inferred from these results. Disruption to agriculture for 6 years from this case was taken as the plant lifetime when calculating the cost of sugar through net present value (NPV) analysis. This could arguably be too conservative an assumption, as the plants would likely stay in operation as agriculture's viability returned.

The destruction to infrastructure, construction budget, and population changes were taken to effectively cancel each other out in target countries. The maximum capacity of plants was considered to be repurposed.

The study considers neither the distribution of biomass and supply chain logistics, nor the geo-political and/or social dynamics of a post–nuclear war state. The global CAPEX for relevant industries such as chemical, power, paper, and brewing were included to give a construction budget of $489 billion per year, which was used as a proxy for the labor and materials available to build the plants (Damodaran, 2020). The study considered the design and organization time (estimated by NREL as 12 months) to decrease to 4 weeks given the severity of the scenario and the similarly quick response times of manufacturers during the COVID-19 pandemic (Betti and Heinzmann, 2020).

3 Theory and calculation

3.1 Component cost comparison

The pulp and paper mill (PPM) was defined as an integrated kraft PPM as detailed by (Larson et al., 2007). Bioethanol production facilities of similar throughput were found to have different volumes depending on whether they use corn or sugarcane as inputs. Corn requires a 46-hour fermentation period while sugarcane only requires 27 hours, giving 1.7 times the tank volume for corn. The scaling of these two facilities therefore led to a different cost for the average plant. The sugarcane facility was modeled on that defined by (Brand et al., 2014), and the corn facility on an earlier report from NREL (McAloon et al., 2000). The brewery costs were based on information regarding the size of ABINBEV's Jacksonville plant (Anheuser-Busch, 2018). Table 1 details the equivalent facility size by ethanol output, when each facility's tank size is scaled to that of the NSM, 61 million gallons per year (MGPY). This scaling results in 46 MGPY for the sugarcane facility, 41 MGPY for the corn facility, 59 MGPY for the PPM, and 45 MGPY for the brewery.

The components present in the process flow diagrams for each type of industrial facility were then compared with the components in the NSM to establish how much equipment was required for a facility to be repurposed into a sugar production facility. The results of this comparison are shown in Table 1, with the justification for these costs outlined in Appendix A. Some unit operations, such as the sugarcane biorefinery's feedstock and handling system, or the pulp and paper pre-treatment, were deemed adequate and therefore given a costing of $0. It is however unlikely that they would be able to operate without upgrading the equipment, analysis of which has been left for future work.

Table 1. Installed cost of expected extra equipment required to repurpose industry to the NSM reference. Values are scaled from 2014 US dollar equivalents to 2020 US dollar equivalents using the Chemical Engineering Plant Cost Index (CEPCI). Dollar values are shown as millions.

			Repurposed industry				
			24/7 construction				
Process area		**NSM reference plant (regular conditions)**	**NSM (catastrophe conditions)**	**Sugarcane Biorefinery**	**Corn Biorefinery**	**Pulp & Paper**	**Brewery**
Area 100: Feedstock and handling		$ 28 m	$ 28 m	-	$ 14 m	$ 7 m	$ 14 m
Area 200:							
- Pretreatment equipment		$ 57 m	$ 57 m	$ 50 m	$ 50 m	-	$ 50 m
- Neutralization/supporting equipment		$ 2 m	$ 2 m	$ 0 m	$ 0 m	-	-
Area 300: Enzymatic hydrolysis/conditioning		$ 61 m	$ 61 m	$ 41 m	$ 41 m	$ 20 m	$ 41 m
Area 400: Enzyme production		$ 13 m	$ 13 m	$ 12 m	$ 12 m	$ 13 m	-
Area 500: Recovery and upgrading (sugar model N/A)		-	-	-	-	-	-
Area 600: Wastewater		$ 49 m	$ 49 m	-	-	-	-
Area 700: Storage		$ 12 m	$ 12 m	$ 1 m	$ 0 m	$ 6 m	$ 0 m
Area 800: Boiler		$ 69 m	$ 69 m	-	$ 69 m	-	$ 69 m
Area 900: Utilities		$ 7 m	$ 7 m	$ 1 m	-	-	$ 7 m
NSM Equivalent Totals (Excl. Area 100)		**$ 298 m**	**$ 298 m**	**$ 105 m**	**$ 186 m**	**$ 46 m**	**$ 181 m**
Equivalent plant size as NSM tank space (MGPY)		61	61	46	41	59	45
Average equivalent industry plant size (MGPY)		61	61	79	79	20	5
Industry totals (scaled to the average size plant for the industry)		**$ 298 m**	**$ 298 m**	**$ 152 m**	**$ 293 m**	**$ 22 m**	**$ 40 m**
24/7 construction cost increase				147% of Industry totals			
Fast construction totals (Average size plant, factoring in 24/7 working costs)		**$ 298 m**	**$ 437 m**	**$ 223 m**	**$ 430 m**	**$ 32 m**	**$ 59 m**
Warehouse	4.0% of ISBL	$ 6 m	$ 6 m	-	-	-	-
Site development	9.0% of ISBL	$ 14 m	$ 14 m	-	-	-	-
Additional piping	4.5% of ISBL	$ 7 m	$ 7 m	$ 7 m	$ 13 m	$ 1 m	$ 2 m
Total direct costs (TDC)		$ 326 m	$ 465 m	$ 230 m	$ 443 m	$ 33 m	$ 61 m
Proratable expenses	10.0% of TDC	$ 33 m	$ 47 m	$ 23 m	$ 44 m	$ 3 m	$ 6 m
Field expenses	10.0% of TDC	$ 33 m	$ 47 m	$ 23 m	$ 44 m	$ 3 m	$ 6 m
Home office and construction fee	20.0% of TDC	$ 65 m	$ 93 m	$ 46 m	$ 89 m	$ 7 m	$ 12 m
Project contingency	10.0% of TDC	$ 33 m	$ 47 m	$ 23 m	$ 44 m	$ 3 m	$ 6 m

Other costs (start-up, permits, etc.)	10.0% of TDC	$ 33 m	$ 47 m	$ 23 m	$ 44 m	$ 3 m	$ 6 m
Total indirect costs		$ 195 m	$ 279 m	$ 138 m	$ 266 m	$ 20 m	$ 37 m
Fixed capital investment (FCI)		$ 521 m	$ 745 m	$ 368 m	$ 709 m	$ 52 m	$ 98 m
Land		$ 2 m	$ 2 m				
Working capital	10.0% of FCI	$ 52 m	$ 74 m	$ 37 m	$ 71 m	$ 5 m	$ 10 m
Total capital investment (TCI)		$ 575 m	$ 821 m	$ 405 m	$ 780 m	$ 57 m	$ 108 m

3.2 Sugar production

The amount of sugar produced in each type of factory was based on calculating the volumetric tank size of each of the reference plants of the industries to be repurposed. The equivalent ethanol output that the NSM reference plant would produce if it were this size was calculated. This was then used with the NSM equivalent output of the industry average size facility to scale each facility's sugar production.

The equivalent ethanol output from the NSM was 231 million liters per year (MLPY). The equivalent output size for each of the industry reference facilities was: corn to ethanol biorefinery 156 MLPY, sugarcane to ethanol biorefinery 175 MLPY, PPM 224 MLPY, and brewery 170 MLPY. These values were then compared to the equivalent output of the average facility size for each industry to give the values in Table 2. An average-sized ethanol biorefinery in the US produces 298 MLPY of ethanol (RFA, 2019). 195 billion liters/year of beer are produced worldwide (Conway, 2018). The average output of a brewery (excluding microbreweries, which make up less than 1% of production volume) is 16.2 MLPY, which equates to an output size of 20 MLPY (Conway, 2018). The pulp and paper industry in Europe has 891 mills and a 20% global market share, giving an expected worldwide number of facilities of 4,325 (CEPI, 2017). The average size of a PPM in Europe was found to be 234,300 tonnes of pulp annually, which equates to an output of 75 MLPY of ethanol for scaling purposes. The average sugar output values for each industry are shown in Table 2.

The output of the facility is limited to 50% during the period equal to 25% of the original build time immediately after construction according to NREL; this period of limited output is defined as the startup period. This is to enable any issues with the facility to be fixed, and in reality, would include periods of full production and times when the facility is switched off.

Table 2. Production, number of facilities, organization time, and construction time. Dollar values are shown as millions.

			Repurposed industry			
		24/7 construction				
	NSM reference plant (regular conditions)	**NSM (catastrophe conditions)**	**Sugarcane Biorefinery**	**Corn Biorefinery**	**Pulp & Paper**	**Brewery**
NSM equivalent CAPEX	$ 298 m	$ 298 m	$ 105 m	$ 186 m	$ 46 m	$ 181 m
Proportion of components pre-existing	0%	0%	61%	62%	85%	38%
Feedstock for average size plant dry metric	0.66	0.66	1.11	1.25	1.25	0.22

(Megatonne/year)						
Cost scaled to average-sized plant CAPEX costs	$ 298 m	$ 437 m	$ 223 m	$ 430 m	$ 32 m	$ 59 m
Total capital investment	$ 575 m	$ 821 m	$ 405 m	$ 780 m	$ 57 m	$ 108 m
Single facility full production (Megatonne/year of carbohydrate equivalent)	0.33	0.33	0.56	0.62	0.11	0.04
Single facility startup production (Megatonne/year of carbohydrate equivalent)	0.16	0.16	0.28	0.31	0.05	0.02
Expected number of average size facilities in the world	N/A	N/A	124	237	4,257	12,018
Organization and design time (weeks)	4	4	4	4	4	4
Construction time (weeks)	86	86	79	86	58	65
Fast construction time - 24/7 construction (weeks)	N/A	28	25	28	19	21

3.3 Total capital investment (TCI)

The key cost that needed to be calculated for each facility was the total capital investment (TCI). This enabled the calculation of the cost of sugar through an NPV analysis and determined how quickly facilities can be built and therefore how fast food production can be ramped up. The TCI for each facility was calculated in a similar way to the NSM, with some alterations to accommodate extra costs associated with repurposing and fast construction methods. NREL's TCI is obtained from Equation 1, where FCI is the fixed capital investment, which comprises the total indirect costs (TIC) and total direct costs (TDC). The TDC here comprises the inside battery limits (ISBL) costs, which are the component and installation costs discussed in Section 3.1, as well as the site development, warehouse, and additional piping costs.

$$TCI = FCI + Land + WC \qquad (1)$$

The ISBL costs shown in Table 1 are in 2014 US dollar equivalents, so they were scaled to 2020 US dollar equivalents using the CEPCI, which increases the values by 5%. These costs were then scaled to the size of the facility using the power-sizing scaling technique (Sinnott, 2005) as shown in Equation 2, where C_2 is the scaled ISBL cost of the target-size plant of capacity Q_2, C_1 is the cost at capacity Q_1, and x is the cost-capacity exponential scaling factor, selected as 0.7. The cost of the target-size production facility was then increased by a factor of 1.47 times, associated with the increased labor cost of the selected fast construction method (i.e., 24/7 construction), as calculated in Section 3.6.1.

$$C_2 = C_1(Q_2/Q_1)^x \qquad (2)$$

3.4 Cost of sugar product

The cost of sugar was estimated by conducting an NPV analysis. The NPV parameters for the regular reference model are included in Appendix B. The value that was changed for the analysis was the plant lifetime, which was changed to 6 years as per the assumptions. The plant was conservatively considered to be fully depreciated over this 6-year period, even though there would be value left in the equipment after this point. If the plants were planned to be shut down after 6 years, components could be built less durably, saving money. However, this is conservatively ignored. The construction period was reduced to that expected for each plant. The concentrated sugar stream values were used, including the additional cost of adding a lignin press with counter-current washing situated after hydrolysis. 70% equity and a working capital equal to 10% of the fixed capital are assumed. All other values were taken from the NSM NPV analysis for its minimum sugar selling price costing (Tao and Davis, 2017). For simplicity, no potential byproduct revenues are considered.

3.5 Time to sugar production

A method was required to estimate the expected reduction in construction time that repurposing might enable. A reference class forecasting correlation was applied to estimate the plant construction time based on construction time data of UK production plants as the reference class. (Martin et al., 2006) proposed that the construction time of factories was logarithmically related to their cost, with an r-squared value of 0.3. On closer inspection, these data had outliers representing very small facilities that took a long time to build, which are also not representative of the facility sizes considered in this work. Once modified to remove these outliers and to include the cost and expected build time of the NSM reference plant, we found the following relationship as shown in Figure 2, where T is the construction time in weeks and C is the cost in GBP. A 0.8 USD/GBP exchange rate was used. Removing the outliers changed the r-squared value from 0.3 to 0.5. This formula gives an expected construction time for the reference plant of 85 weeks. The NREL report estimated a 104 week total construction time including design; however, given that NREL based this time upon a small dataset (including the construction time for a $1.5 billion oil refinery of 104 weeks), we used the data from Figure 2 to calculate a new estimate for the NREL plant, resulting in a construction period of 84 weeks.

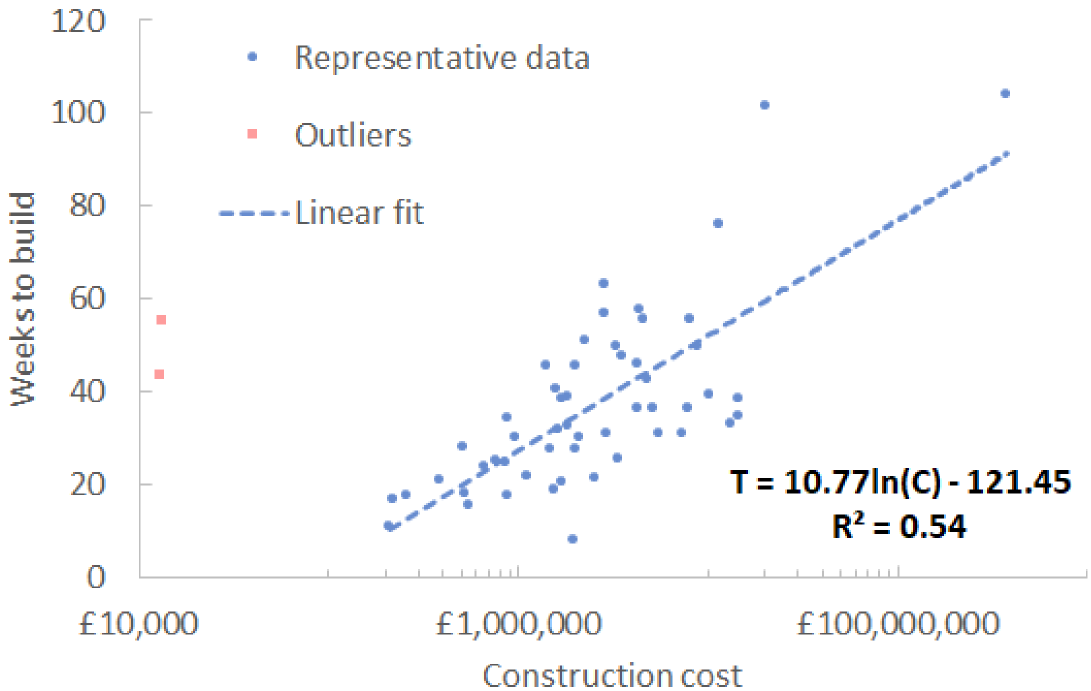

Figure 2: Construction time correlation as a function of cost, based on UK factories with data from (Martin et al., 2006).

3.6 Fast construction

Five methods for decreasing the construction time were considered: 24/7 construction, modular construction, A+B bidding, overmanning, and overtime. Of these methods, 24/7 construction produced the greatest acceleration with reasonable penalty, and was therefore selected as the construction method to be used during the scaling calculations. The methodology for fast construction time and cost estimation developed here has been useful in several other works (García Martínez et al., 2020, 2021c, 2021d, 2021b).

3.6.1 The 24/7 construction method

The 24/7 construction method involves constructing the factory during all hours available during the week. Constructing 24 hours a day avoids the problems of overtime by removing the overtime hours and assigning 3 shifts of 8 hours each day to cover a 24-hour period (Hanna et al., 2008; Ibbs and Vaughan, 2015). There are inefficiencies associated with 24 hours construction; (Hanna et al., 2008) developed a correlation for productivity loss of 24 hours shift work, described by Equation 3:

$$PL = 0.22052 + 0.07152 \cdot ln(S_f) \quad (3)$$

Where S_f is the proportion of shift work, defined as the hours worked by an additional group of workers whose work on a project begins after the first workforce has retired for the day. The expression was developed for a 24 hour schedule during workdays, meaning 5 out of 7 days a week. To account for the full 7 days a week of 24/7 construction, there would be a requirement for just over four shifts (where a single normal shift would have 8 hours of work, five days a week). In summary, ¾ of the total work hours would be at inconvenient times. Thus, to account for the reduced amount of shift work during hours outside of the regular shift schedule, a 75% shift work proportion is applied. Using this value in Equation 3, we determined that the loss in productivity would be 20%. We determined our ideal reduction in completion time (T_i) that the shift work would produce:

$$T_i = Budgeted\ hours\ /\ Total\ hours\ with\ shift\ work \quad (4)$$

Here we assume a 40-hour budgeted work week, compared to a total of 168 weekly work hours with shift work, giving a T_i of 24%. We can then apply the productivity loss from above to find the actual reduction in completion time, (T_a):

$$T_a = T_i \cdot (1 - PL) \quad (5)$$

This gives a reduction of 32%. Assuming that 3 of the 4 shifts are paid 120% more for working outside normal work hours, our labor cost is increased by 460%; however, when we factor in the actual reduction in T_a, this becomes 147%.

The time of construction is therefore reduced to 32% of the original time, while the total labor cost is increased by 1.47 times. The budget for constructing these plants is limited, so the increased costs means less plants can be created. However, given the significant reduction in construction time, this means the plants can be built faster and food production can start sooner.

3.6.2 Modular construction

Many facilities today that need to be constructed as quickly as possible will generally use modular construction. Modular pieces such as walls or compartments are built off-site in factories, shipped to the construction site, and then assembled into the final structure (Lawson et al., 2012). Mass production of the modules and the minimum amount of construction labor required makes modular construction inexpensive as well as fast (Fawcett et al., 2005). Constructing in a modular fashion can be completed 20–50% sooner (Bertram et al., 2019); however, this method would require scaling other factories to construct the modules.

3.6.3 A+B bidding

A+B bidding is a method for selecting a company for a project or contract. The company must submit two sections to their bid for the contract, the first based on the cost and the second on the time to complete (Lee and McCullouch, 2009). The cost is determined by adding the base contract price to the construction time, multiplied by a set expense rate. This rate would effectively be the daily cost to society of not having the production that the new facility would offer. This is an indirect method for speeding up the construction of a facility, so this method could be used to ensure that companies are incentivized to work as fast as the other techniques suggest is possible.

3.6.4 Overmanning

Another method considered was overmanning, which is simply adding more workers on site than is typically used for a given project. Overmanning is limited as the increased number of workers causes crowding and management difficulties (Hanna et al., 2007). While overmanning is effective for decreasing the construction time, the benefits are outweighed by the added costs. Previous work has shown the efficiency loss associated with overmanning mechanical and sheet metal laborers (Hanna et al., 2007) to be calculated by Equation 6:

$$L = -0.305 + 0.116 \cdot N_p / A_v + 0.163 \cdot log(N_p) \quad (6)$$

Where L is the lost efficiency of work due to the overmanning, N_p is the number of workers during overmanning and A_v is the typical number of workers on a given project. We took the expected number of workers to build the NREL plant (1,720) then equally divided this by the 3 main worker trades: electrical, mechanical, and civil, giving an A_v of 573. If each trade were doubled for overmanning, this gives an N_p of 1,147, giving the efficiency loss as 43%. We can now find the actual reduction in completion time, T_a. Thus, if the ideal labor factor, I, is 50% due to having doubled the workers, then as per Equation 7 the efficiency loss causes our actual time to be:

$$T_a = I \cdot (1 - L) - 1 \quad (7)$$

Where I is the ideal labor factor, which is the ratio of A_v to N_p, which is 50% as we have doubled the workers. This yields a T_a value of 87%. The increase in cost for overmanning is greater than that of 24/7 construction and the time saving is lesser, so overmanning was ruled out. Overmanning can potentially be combined with 24/7 construction, but this was not accounted for in the calculations.

3.6.5 Overtime

Overtime is an acceleration method where the construction labor force works longer hours in order to complete more work, but at an increased cost for the extra work. In addition to the costs of overtime labor, the added hours to the workers results in lower morale and poorer-quality work due to worker fatigue (Ibbs and Vaughan, 2015). Worker productivity indices range from 0.95 to 0.75, if a worker completes overtime of 50 hours or 84 hours in their first week of overtime respectively (Carter, 2017). In the 10th week of working these hours the productivity indices drop for each to 0.72 or 0.42 respectively. After the 6th week of working a 50-hour week, the productivity of an overtime worker drops to 0.76, exceeding the 20% productivity loss incurred during 24/7 construction. Thus, overtime was not selected as the fast construction method.

3.7 Ramp-up speed estimation

We define the ramp-up speed as the increase in food production over time when continuously building as many sugar production factories as possible with the available resources. Ramp-up speed is constrained by the availability of resources such as qualified labor and capacity for equipment construction, among others. We roughly account for these constraints by limiting the budget that can be effectively applied to 24/7 construction of lignocellulosic sugar plants to a value of $489 billion per year (Damodaran, 2020). This value is equivalent to the CAPEX budget of the chemical and related industries, whose resources we consider could be redirected towards ramping up the sugar production in a reasonably efficient manner. Then, using the factory construction cost and time results, the increase in food production when constructing the maximum possible number of production plants with the available budget is obtained. The production ramp-up speed of lignocellulosic sugar is described here in terms of the proportion of global human caloric requirements that could be fulfilled by the produced sugar. An applied example of this ramp-up speed estimation methodology is described in depth in the supplementary material of (García Martínez et al., 2021d).

4 Results and discussion

4.1 Cost of and speed of sugar production

The cost of sugar produced by a plant depends mainly upon its size; for repurposed facilities the cost also depends on the savings due to relevant existing components, given that CAPEX costs per kilogram dominate the other variable cost components, and that CAPEX costs are the most relevant to consider as they are the dependent variable in this analysis. The capital costs for the NREL plant and for an equivalent-size plant scaled from each repurposed industry's reference plant are shown in Figure 3. The ramp-up speed of food production—estimated as per Section 3.7—is shown in Figure 4 for each repurposed industry and their sum, the latter of which is compared with the speed of 24/7 construction of new factories in Figure 5.

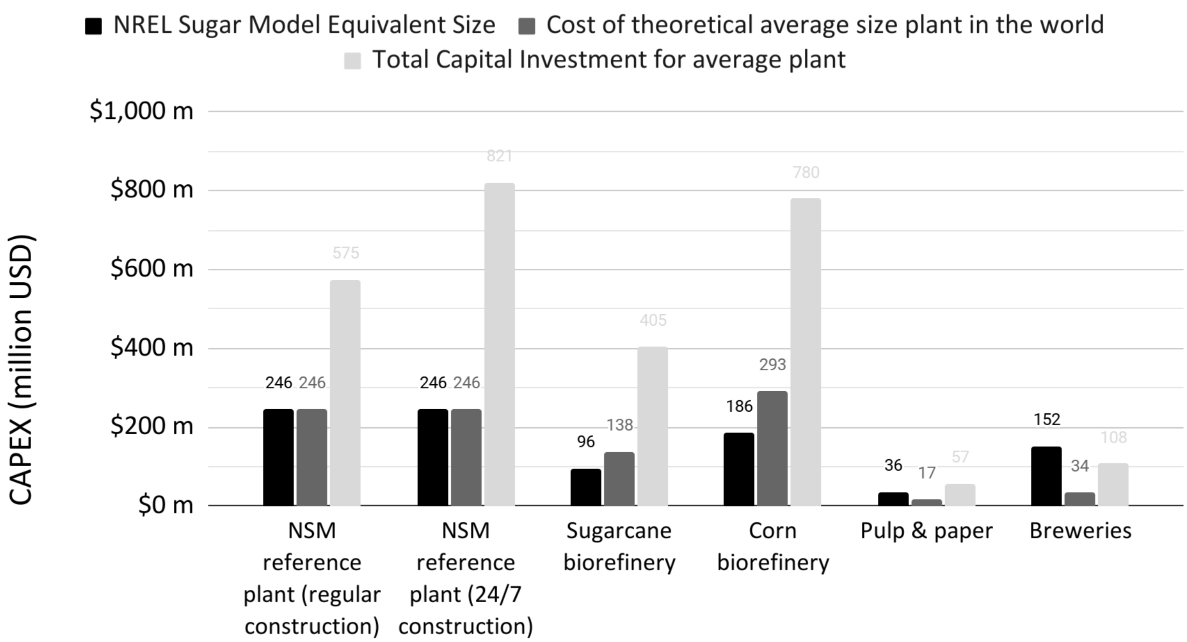

Figure 3. CAPEX and TCI required for building or repurposing each different type of plant, including a comparison with the cost of regular construction speed.

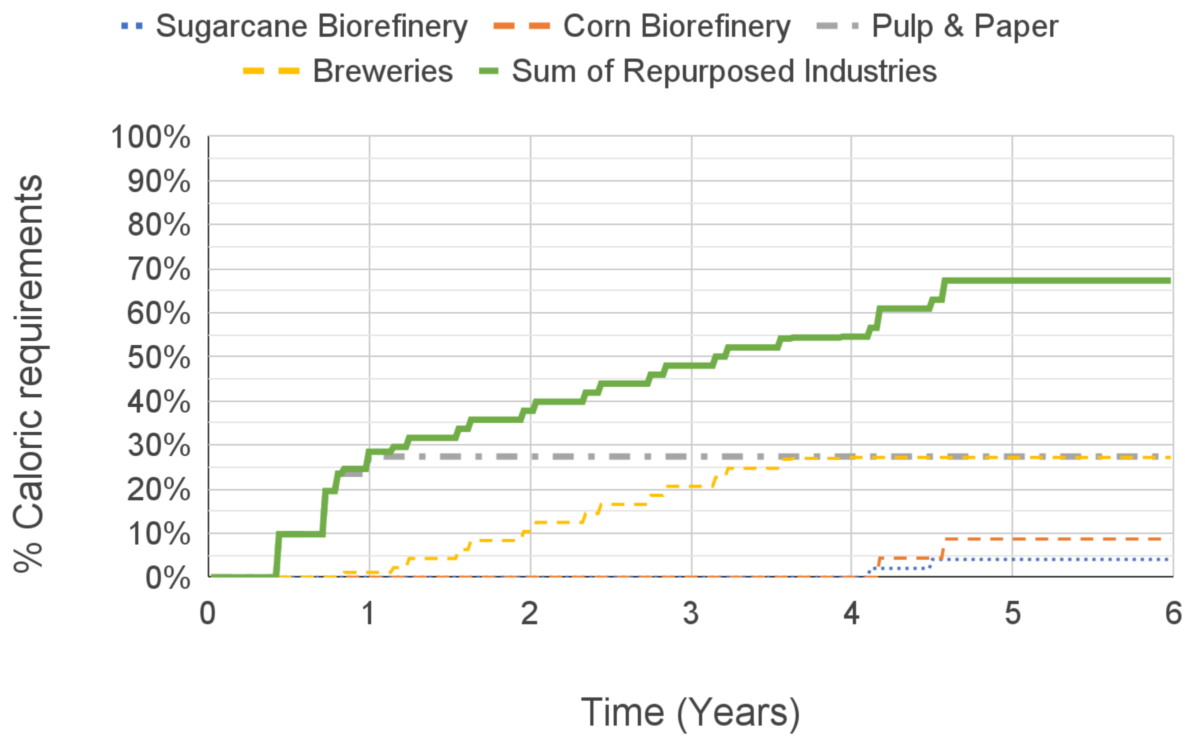

Figure 4. Ramp-up speed of lignocellulosic sugar production via repurposing of existing factories as a proportion of the amount of sugar required to fulfill the global caloric requirements using the global CAPEX budget ($489 billion) of chemical and related industries.

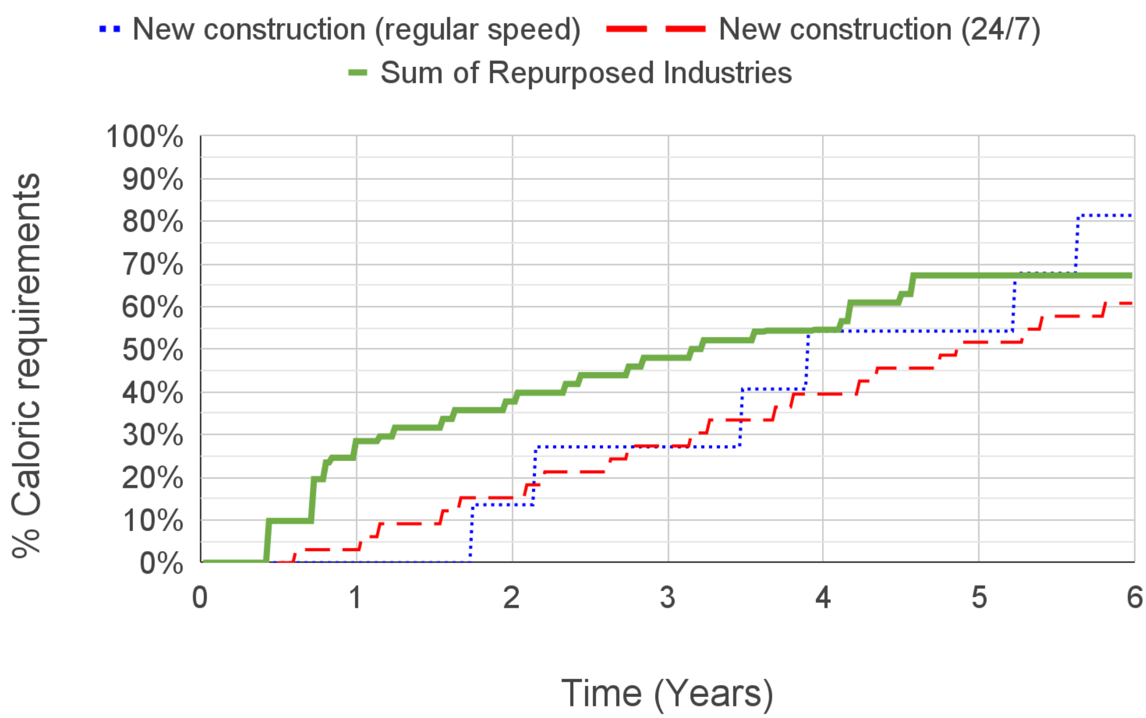

Figure 5. Comparison of the production ramp-up speed between repurposing existing factories, building new factories quickly during a catastrophe, and building new factories at regular speed.

The expected production cost in the NSM was $0.43/kg (dry sugar mixture) in 2020 US dollar equivalents for the concentrated sugar stream for an expected plant lifetime of 30 years and an internal rate of return of 10%. The cost is conservatively high compared to other analyses of sugar production from lignocellulosic biomass, not only in terms of production cost, but also in terms of capital cost per unit of installed production capacity (Michels, 2014; Moncada et al., 2018; Ou et al., 2021), These are generally higher than the historical sugar spot prices in the last five years, ranging between $0.22-0.50/kg (Macrotrends, 2021).

The expected production cost increased to $0.87/kg (dry carbohydrate equivalent) when factoring in the digestibility of the sugar products and the catastrophe conditions we propose: a) the 6-year average plant lifetime (active only during the nuclear winter period), b) the increased cost of 24/7 construction, c) 70% equity, and d) working capital equal to 10% of the fixed capital investment. Doubling production costs to achieve an estimate of retail costs gives $1.74/kg for a new facility.

Under these assumptions, repurposing sugarcane and corn biorefineries would be expected to produce sugar at a retail cost of $0.92/kg and $1.16/kg respectively. Repurposed pulp and paper, at $0.82/kg, is the cheapest to produce and the fastest to be up and running, suggesting labor and components should be directed towards repurposing these plants first. Repurposing PPM to produce lignocellulosic sugar is the fastest option due to the presence of more repurposable components and to the small size of the plants, while the high repurposability also makes it the cheapest. Repurposing breweries is the next-fastest option, but at $1.26/kg are the most expensive. The average cost of sugar for the repurposed plants is $1.04/kg, a very low cost per person, given that a daily caloric intake of 2,100 kcal/day could be fulfilled at a price of $0.55. By comparison, using greenhouses in the tropics during a sunlight reduction GCR scenario is expected to increase the cost of produce by ~$2.30/kg (Alvarado et al., 2020). The cost values are summarized in Table 3.

Table 3. Wholesale production cost and expected retail cost of the lignocellulosic sugar product for different new construction and factory repurposing scenarios, in USD per unit of dry carbohydrate equivalent.

	NSM reference plant (regular conditions)	**NSM (catastrophe conditions)**	**Sugarcane Biorefinery**	**Corn Biorefinery**	**Pulp & Paper**	**Brewery**
Wholesale cost ($/kg, dry)	$0.52	$0.87	$0.46	$0.58	$0.41	$0.63
Retail cost ($/kg, dry)	$1.04	$1.74	$0.92	$1.16	$0.82	$1.26

Equation 2 is estimated to have a ±30% accuracy range when estimating the CAPEX value of plants costing $1-100 million (Peters et al., 2003). To account for some of the plant costs estimated here being outside that range, a ±50% sensitivity in the CAPEX was incorporated to study the effect on the estimated retail price. The range of retail prices for the repurposed factories went from the original $0.82-$1.26/kg to a range of $0.70-$1.60/kg. These changes are not significant for our purposes since, even with the highest cost estimate of $1.60/kg, over 97% of the global population would still be able to afford the sugar equivalent to 100% of the caloric intake based on current incomes (Denkenberger et al., 2019).

4.2 Proportion of global human caloric requirement produced

The minimum global calorie requirement in terms of carbohydrate equivalent mass is 1.7 gigatonnes/year, based on the average Atwater factor of 4 kcal/g for carbohydrates (Merrill and Watt, 1955), a global population of 7.8 billion people, and the average 2,100 kcal/day/person (WHO, 2004). This figure assumes no human-edible food is fed to animals or turned into biofuels, and assumes 1/3 as much food waste as at present (Denkenberger and Pearce, 2014), 12% of the total. Figure 5 shows the breakdown of the proportion of world calorie requirement that would be produced if the relevant global industries' (chemical, power, paper, and brewing) CAPEX budget of $489Bn is effectively used to construct either the NSM reference plant at its expected build schedule or the the 24/7 build schedule, or instead is used to build the fastest available repurposed industry facility. Figure 4 illustrates the sugar production that each repurposed industry would contribute. The sum of the repurposed industries would be much quicker to come online than the new builds, beginning start-up production (i.e., half of the installed capacity) after ~5 months and reaching 28% of the global calorie requirement after ~9 months. Given how sugar currently represents 11% of the world's calorie consumption (Shahbandeh, 2020), the world's current sugar needs could be met after 5 months. It may be necessary to continue ramping up production if there are not sufficient amounts of other resilient foods available. The first plants that should be repurposed, pulp and paper mills, are very inexpensive to repurpose as they already contain 85% of the components required. After this, the sum of the repurposed industries slows as the other industries with fewer comparable components are repurposed. After ~4 years, the repurposed industries would reach their capacity, after which time switching to fast construction of the of new plants would be logical if there were still capacity for sugar to be consumed in quantities exceeding 70% of global human caloric requirements (e.g., if the sugar were used as animal feed). Given ongoing research efforts into resilient foods (ALLFED, 2017; LaJeunesse, 2020; Tzachor et al., 2021), it is expected that this sugar production capacity would not need to be fully employed even in the most severe sunlight reduction scenarios.

Naturally, the use of sugar as a single source of calories is not feasible for humans. The US Institute of Medicine has proposed an upper limit of at most 25% of the total energy intake from added sugar (Institute of Medicine, 2005). Figure 6 shows the ramp-up speed in terms of the proportion of this sugar intake equivalent to 25% of total calories. At the expected repurposing speed, reaching this production could be achieved within 1 year. Other resilient foods, such as those mentioned in Section 1, would be required to complement the lignocellulosic sugar for a balanced diet in the proposed GCR scenarios. Combined production of lignocellulosic sugar and leaf protein concentrate from leafy biomass feedstocks could be an interesting future research avenue, since it could allow for simultaneously obtaining a more valuable food product in terms of nutrition.

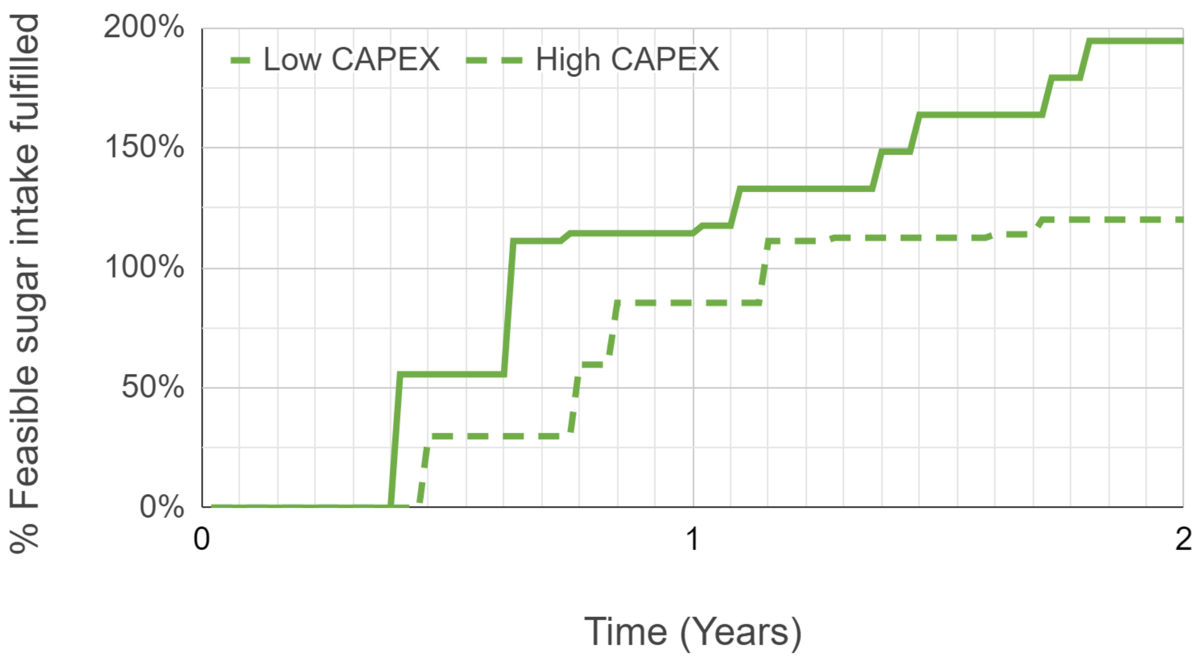

Figure 6. Ramp-up speed of lignocellulosic sugar production via repurposing of existing factories as a proportion of the maximum recommended sugar intake of 25% of total calories. Values are given for the low and high ends of the capital cost as per the sensitivity analysis.

A sensitivity analysis was performed on the ramp-up speed results as shown in Figure 6 based on the same ±50% sensitivity in the CAPEX as was done for the retail costs. The result points to the robustness of the main conclusion of the present work: according to the component comparison analysis, by repurposing existing factories for production of sugar from lignocellulosic biomass, a considerable amount of the global food requirement could be produced relatively fast (<1 year), which in turn probably represents a significant fraction of the maximum amount of sugar that people can eat without risking a potentially unbalanced diet.

If reaching over 100% of global human caloric requirements were desired, e.g. for use as animal feed, the fastest possible way would be to build ~5,200 or more new plants simultaneously. Each plant would be expected to reach start-up in just over 5 months, and would have a 50% capacity production of ~0.33 megatonnes/year/factory, at a cost of $4.2 trillion. It is inferred that this would be fiscally possible, given that the US stimulus package for the COVID-19 pandemic was $3 trillion, distributed over 4.5 months (Lowey, 2020). Instead, the limiting factor would likely be sourcing materials, equipment and skilled workers.

The current analysis is deliberately conservative in that the capital cost of 24/7 construction during a catastrophe is estimated as 1.47 times the original, due to the increase of 1.47 times the labor cost introduced by 24/7 construction, even though the labor cost typically accounts for less than 50% of the capital cost (Gichuhi, 2013; Sullivan, 2019). Since the speed at which the factories can be created in turn depends on this capital cost value, the speed is proportionally underestimated. This partly addresses uncertainties in the availability of qualified labor during the catastrophe scenario.

4.3 Biomass and fuel availability analysis

Given the increase in food price during a nuclear winter GCR scenario, the consumption of nonessential goods will fall dramatically, reducing energy demand in many sectors. However, energy demand will likely increase in other sectors, including food. Therefore, there may be increases in fuel demand, so one may question whether there would be sufficient biomass availability for significant scaling of lignocellulosic sugar production. A global lignocellulosic biomass and fuel availability analysis was performed in order to ascertain this, which can be found in Appendix C. The amount of dry tree biomass required to cover 100% of the annual human caloric requirement via lignocellulosic sugar production is estimated at 4.66 Gt/year. This amount is found to be equivalent to ~21% of global annual tree removals or ~74% of the global agricultural residue production, indicating that current biomass capacity is likely sufficient to reach a significant food production level. However, biomass harvesting capacity would likely need to be scaled up in a sunlight reduction scenario. The annual biomass requirement is equivalent to ~0.5% of the total global plant biomass, indicating that the amount of biomass itself would not be a bottleneck to lignocellulosic production ramp-up. The degree of fuel consumption required to harvest and chip the amount of biomass necessary to fulfill the entire global caloric requirements via lignocellulosic sugar is estimated at only ~1% of current liquid fuel production, indicating this would not be a bottleneck either (see Table C1).

4.4 Preventing global famine

The results show a significant step forward to achieving food security in the face of the most extreme agricultural shortfalls caused by a catastrophic scenario, such as nuclear winter. In this scenario, or indeed for other sunlight reduction GCR events, humanity would be faced with a difficult period once food stockpiles would run out after 4–6 months (Baum et al., 2015). Sugar biorefineries could have a large role to play in the survival of humanity in such scenarios, as suggested by the result of ~28% of the minimum global caloric requirement that could be covered in 9 months by repurposing existing factories.

A previous order-of-magnitude estimate suggested that 100% of global human caloric requirements could be provided by sugar after one year (Denkenberger and Pearce, 2014). Though the more detailed estimate here gives a considerably lower percentage, sugar could be produced more quickly if the construction budget from the physical manufacturing industry could be effectively leveraged for repurposing facilities and using fast construction methods to build new plants, but this would increase costs.

The most promising industries that have been identified for repurposing; namely biorefinery, pulp and paper, and brewing, differ in terms of their future market projections. Pulp and paper is expected to have very moderate growth (Tiseo, 2021), while biorefinery (GVR, 2020) and brewing (TBRC, 2020) are expected to see significant growth. These last two are projected to grow at a rate higher than the global population, which would improve the prospects of repurposing for lignocellulosic production ramp-up in the near future. Despite the current low volume of cellulosic ethanol production (2nd generation biorefinery), it is possible that significant production increases will take place in the coming decades (Susmozas et al., 2020), allowing for quickly obtaining significantly more sugar by inexpensively repurposing these facilities in a catastrophe scenario.

A reasonable criticism may question the pace at which these facilities could be repurposed. A historical example of scaling industrial production occurred in the US during WWII. On October 15, 1940, a US government defense commissioner attended the Automotive Manufacturers Association meeting, to place an order for $9.2 billion (2020 US dollar equivalent) worth of aircraft items never seen or manufactured by the automobile industry (ACEA, 1950). By March 15, 1941, a single division of General Motors was producing 350 aircraft engines/month. Moreover, this took place during the period of WWII that the US was not actively involved. Less than 4 weeks after the attack on Pearl Harbor took place, the automobile industry body reformed as the Automotive Council for War Production, resolving "unlimited cooperative effort to speed production of war material for victory." In the first 5 weeks of 1942, the US government placed contracts equivalent to the value of the previous 2 years. In the following 6 months, the value of the items produced grew from $11.7 billion (2020 US dollar equivalent) in January 1942 to $28.2 billion (2020 US dollar equivalent) by July, increasing by 2.4 times. A more recent repurposing has been the variety of industries repurposing to produce equipment to be used to address the COVID-19 pandemic. Perfume, textiles and electronics factories have been repurposed for producing hand sanitizer, face masks and ventilators respectively (Poduval et al., 2021). This repurposing took place in a matter of weeks, with the most complex products taking 4–12 weeks to get production to a point that it is ready to scale (Betti and Heinzmann, 2020).

The budget figure used in the scaling of these industries was the global capital expenditure of relevant industries, $489 billion. While this is the amount of relevant equipment production and labor skilled in the construction of plants for the chemical, power, paper, and brewery industries, other industries may be able to retrain and retool as the automobile industry did, which would unlock access to more of the $2,702 billion global annual CAPEX of all manufacturing (Van der Meer et al., 2017), which could increase the production ramp-up by a factor of 4.5 times. Further increases could be achieved by redirecting building and/or road construction resources. The historical precedent of another wartime effort may enable the amount of trained labor to be expanded further. In 1918, women who were previously untrained produced 75% the quantity of manufacturing work that the previous skilled labor force had produced, after these women underwent only 5–6 months of training (Turner, 1918). Other trades that were found to scale up far faster included welding, which required only 30 days for the basics; however, expert welders take far longer to be trained.

This undertaking would need government and/or industry involvement at regional and national scales to organize effectively. In this study, NREL's expected design and organization time of 52 weeks was reduced to 4 weeks given that during the COVID-19 pandemic, the time it took for the industries to convert and scale production was 4–12 weeks. If the delay before starting construction of new plants was longer, that would be mathematically equivalent to shifting the ramp-up curves to the right, slowing the entire process.

Certain organizational and scoping work could be taken ahead of time to reduce this time, such as establishing which regions are best suited to repurposing and which ones would be best suited to new build plants, such as suggested in a previous cost-effectiveness analysis (Denkenberger and Pearce, 2016). Further work could establish industry alliances to create ready-formed networks before a nuclear war. New builds, while not as quick to bring into production using the current capital resources devoted to the construction of similar industries, are flexible in location and could scale proportionate to the budget allocated to them, materials permitting. Other potentially useful resources for expediting lignocellulosic sugar production ramp-up in a GCR scenario that could be taken prior to a catastrophe include: a coordinated response plan for materials and labor deployment to a collection of pre-approved sites, an open-access generalist detailed engineering design package, and an expert guide on how to successfully build and operate the plants if the lignocellulosic sugar market reaches maturity in the future.

4.5 Limitations of the study

Ramp-up speed estimates as described in this study depend on 1) resource availability, as discussed in Section 4.4, 2) plant CAPEX (be it normal or fast construction, or repurposing), and 3) plant construction and start-up times. Forecasts could be improved with a better dataset for reference class forecasting of construction time. A dataset based on a better reference class, such as chemical and food production factories around the world, should yield more precise estimates than the dataset based on UK factories.

The accuracy of the CAPEX estimation method is estimated as between 20-30% for chemical plants in the range of $1-100 million (Peters et al., 2003), which puts the final scaled CAPEX of the plants out of range (except PPM and breweries). However, the method is considered to be internally consistent, enabling accurate comparison between the facilities used in the study (Martinkus and Wolcott, 2017). In any case, this study went into a deeper "tactical-level" assessment by considering the individual component costs within each unit operation as discussed in Appendix A, giving greater confidence in the results. Additionally, as previously mentioned, capital and product cost results of this analysis are conservative in comparison with techno-economic analyses from literature.

The repurposing analysis is overall limited by the theoretical nature of the component comparison methodology upon which the repurposing CAPEX values are based. Also, the time of repurposing a facility is estimated using the same forecasting methodology as for new construction of plants, which may not be as appropriate. Empirical fast construction and repurposing pilot plant studies would yield more precise values of repurposing and fast construction costs and times. Given the apparent potential of lignocellulosic sugar as a resilient food for GCRs, further research on these issues appears justified not only for increased precision but also to develop the technology to the degree necessary for fast response in case of catastrophe, prior to its occurrence. Indeed, a main takeaway of the analysis of COVID-19 repurposing efforts published by the United Nations Industrial Development Organization (UNIDO) is that we should "[...] leverage on proven designs and methods; starting from scratch or trying to 'reinvent the wheel' can lead to significant delays" (López-Gómez et al., 2020).

Ramp-up speed values as given in figures 4-6 also depend on the target food production value. Global caloric requirements were estimated assuming 1/3 as much food waste as at present (12% of total food production) with no human-edible food fed to animals or turned into biofuels. Accuracy could be improved with more precise inputs on the actual calorie consumption per capita in the catastrophe scenario, including things like biofuel production, food used as animal feed, production and distribution losses and household food waste. Future research will address these issues.

Other less technical sources of uncertainty are present in the analysis. Conditions would change considerably in the aftermath of a nuclear war, both in target and non-target nations, likely much more than in the supervolcanic eruption or astronomical object impact scenarios. The potential collapse of key institutions such as currency, government, and the trust itself in target nations would change market conditions worldwide. The time it would take for individual government, military, industry, or civil society groups to organize would depend on many factors, such as whether they are on target or non-target states, how industrialized the state is, pre-existing organizational capabilities, and technical capabilities. Infrastructure destruction, supply chain logistics, and changes to global markets associated with the catastrophe would likely reduce the percentage of global human caloric requirements that lignocellulosic sugar could provide. However, a detailed analysis of each of these factors is beyond the scope of this paper. Future research will address issues such as these, including adequate financial assumptions, market equilibrium and the degree of: global coordination, global trade, income continuation, or governmental intervention (e.g. price fixing or rationing).

Infrastructure and industrial capabilities are considered to remain largely functional around the world in the proposed sunlight reduction GCR scenario, which would allow for the construction and continued operation of lignocellulosic sugar production plants. This is a reasonable expectation for regions not targeted by nuclear attacks, even in a nuclear winter scenario. If instead significant loss of global industry were to occur simultaneously with the reduction of incidental sunlight—for example, due to nuclear electromagnetic pulse attacks—a different set of resilient foods would be required, as described in (Denkenberger et al., 2017).

5 Conclusions

Lignocellulosic sugar shows significant potential as a food solution resilient to abrupt sunlight reduction catastrophes such as a nuclear winter, and ought to be included in response plans to these risks. It was found that, by repurposing existing factories to produce sugar from plant biomass, a very significant share of the global food requirement could be produced quickly and inexpensively during a collapse of agriculture. This justifies a need for further research on the topic, such as repurposing and fast construction pilot studies and food safety studies.

This study found through component comparison to the NREL 2017 Biochemical Sugar Model that sugar biorefineries, corn biorefineries, and pulp and paper factories lend themselves well to repurposing for lignocellulosic sugar production, with 61%, 62%, and 85% of ISBL unit components present respectively.

A comparison of fast construction methods was performed to conclude that 24/7 construction is the most adequate method to expedite construction of food production plants in the proposed nuclear winter scenario. Constructing these facilities on a 24/7 schedule is estimated to reduce the time to food production to 32%, at an increased labor cost of 1.47 times. This analysis, first described here, has been used as a basis to estimate fast construction costs for other resilient food production facilities such as microbial protein or synthetic fat.

By repurposing pulp and paper mills, current global sugar demand could be fulfilled after 5 months, helping to bridge the gap between food stockpiles becoming exhausted after the agricultural catastrophe and other resilient foods scaling up. Estimations suggest that an amount of sugar equivalent to a large share of the global caloric requirements of the human population (~28%) could be achieved in 9 months at a cost of $0.82/kg. This would be more than sufficient to feed the maximum recommended amount of sugar to the entire human population. Global lignocellulosic biomass availability does not appear to be a constraint to production ramp-up.

Expected investments in 2nd generation biorefineries in the coming decades imply positive future prospects for the potential of lignocellulosic sugar as a resilient food solution for global food catastrophes.

Acknowledgements

Thanks to Ray Taylor, Kyle Alvarado, Marisa Jurczyk, Liz Specht, Lori Giver and Loula Merkel for useful discussions. Thanks to Megan Jamer for editing.

Funding

The funding for this work was provided by the Alliance to Feed the Earth in Disasters (ALLFED).

6 Appendices

Appendix A – Component comparison

The production plants were compared on a component basis with the NREL 2017 Biochemical Sugar Model, the components of which can be found in Appendix A of (Humbird et al., 2011). These are the comparisons made with the plants described in Section 3.1, and shown in Table 1. The values are in 2020 US dollar equivalents as adjusted from 2014 US dollar equivalents by using the CEPCI, which gives an increase of 5%, and so these values will not correlate directly with those in Appendix A of (Humbird et al., 2011), as these were expressed as 2009 US dollar equivalents. As noted in Section 2.2, where equipment has been given a value of $0, this shows that it was deemed to be suitable for repurposing; however, further work would be needed to ascertain if it would need upgrading, and if so how much this would cost.

Area 100: Feedstock and handling

The full feedstock handling area would cost $25 million to build and would include components for accepting, weighing, storing, and transporting feedstock.

The sugarcane converted biorefinery would need no feedstock handling equipment, given that a sugarcane plant of equivalent tank size would be handling around 1.5 times the amount of the NSM. The sugarcane equipment would be sufficient to handle agricultural residues but may need upgrading to handle timber. In the corn biorefinery, the scales and conveyor belts could be repurposed, but a feedstock storage system would be required. PPM and breweries would require feedstock storage systems as well.

Area 200: Pretreatment

The pretreatment area would include components to break down the hemicellulose carbohydrates into soluble sugars to facilitate Area 300's enzymatic hydrolysis. These components would include sulfuric acid tanks, pumps, and plug screw feeders. The NSM used a relatively mild pretreatment to ensure the efficiency of the ethanologenic bacteria, but a more severe treatment could be used to increase the yield of the sugars, as these bacteria would not be necessary in the sugar process. This was conservatively not accounted for. The majority of pretreatment is required for the sugarcane converted biorefinery repurposing, except for some pumps, heaters, and condensers. It may be possible to repurpose juice extraction as a milling process, but this was conservatively ignored. The liquefaction tanks in the corn biorefinery could be repurposed as flash and ammonia tanks, along with the corresponding pumps and heaters. Pulping is essentially a type of pretreatment, so this entire area is covered for kraft PPM, however non-kraft PPM would have a lower yield of sugars given the lower severity factor that can be achieved (Binod et al., 2011). Breweries would also require installation of pre-treatment equipment.

Area 300: Enzymatic hydrolysis

The enzymatic hydrolysis area would contain equipment for the saccharification (breaking down oligomers into monomers) of cellulose into glucose, using the enzyme cellulase. It is assumed that the fermentation tanks in sugarcane and corn ethanol plants would be repurposed for enzymatic hydrolysis. For the enzymatic hydrolysis area, the brewery, sugarcane, and corn ethanol plants would require the sugar concentration components and lignin filter to be purchased at a cost of $37 million. The lignin residue is highly variable in size and difficult to dewater, and thus would require a more extensive filtration system than is often present at these sites. The PPM would already have the filters and evaporators from this area but would need the rest of the components, at a cost of $18 million.

Area 400: Enzyme production

The enzyme production area produces the cellulase enzymes that are used in Area 300. Both sugarcane and corn ethanol biorefineries would require most of the enzyme production equipment, but each could repurpose their seed fermenters to act as the seed fermenters of this process, saving $0.8 million/plant. PPM would require the entire equipment from this area. Thanks to the high quality of brewing equipment, it is likely that breweries would be able to support complete enzyme production from their yeast production assets.

Area 500: Recovery and upgrading

This area deals with the recovery of ethanol from the sugar and therefore is not relevant for the sugar plant.

Area 600: Wastewater

A number of waste streams would be generated from the sugar facility and these would be processed in Area 600 before release to the environment. All of the facilities would have wastewater treatment included. It is not immediately clear if the size and scope of these facilities would be sufficient for a cellulosic sugar facility. However, our analysis uses the size of each facility's tanks as a basis for sizing the cellulosic facility, resulting in similar water usage. It is possible that some recycling or evaporation of water may be necessary if the size of the wastewater facility is not sufficient. However, for this initial assessment, we assume no additional cost is needed. This seems a reasonable assumption given that in the emergency situations described, wastewater treatment could be seen as less than essential. Further work could include scoping the required changes and looking at how much water could be recycled.

Area 700: Storage

This area denotes all the bulk storage for chemicals used in the process. Assuming that the ethanol storage tanks could be repurposed, the sugarcane plant would require $1 million. The corn plant would only require a sulfuric acid tank at a cost of $0.2 million. No product tanks were assumed to exist in PPM, therefore requiring $6 million. Breweries would require sulfuric acid tanks in addition to their existing equipment.

Area 800: Boiler

This area would house the boiler/turbo generator, which would produce electricity from organic by-product streams such as lignin and un-converted cellulose. The boiler/turbo generator that would run on the bagasse in the sugarcane should be sufficient, as it would already be designed to handle biomass-based solids. The study assumes the boiler would be purchased for plants using corn and for breweries, which would have the advantage of burning the lignin produced and being able to utilize the waste heat. The PPM would have an appropriately sized boiler already present to burn the lignin removed during pulping, while breweries and plants using corn would require one to be installed.

Area 900: Utilities

Area 900 includes all the utilities required to run the plant (apart from steam, which is included in Area 800). The sugarcane reference plant did not detail all utilities but was expected to have all utilities other than the $1 million chilled water package. The corn ethanol plant and PPM were found to have all utilities onsite.

Appendix B - Net present value analysis parameters

Table B1. Net present value analysis parameters

	NREL 2017 Biochemical Sugar Model		Repurposed industries
	Regular build time	24/7 build time	24/7 build time
Plant life	30 years	6 years	6 years
Discount rate	10%		
General plant depreciation	200% declining balance		
General plant recovery period	7 years	6 years	6 years
Steam plant depreciation	150% declining balance		
Steam plant recovery period	20 years		
Federal tax rate	35%		
Financing (% equity)	40%	70%	70%
Loan terms	10-year loan at 8% APR		
Construction period	2 years	27 weeks	As per table 2
Working capital (% of fixed capital investment)	5%	10%	10%
Start-up time	3 months	3 months	25% regular build time
Revenues during start-up	50%		
Variable costs incurred during start-up	75%		
Fixed costs incurred during start-up	100%		

Appendix C - Biomass and fuel availability analysis parameters and results

Table C1. Summary of the tree and fuel biomass availability analysis used to estimate the amount of biomass and liquid fuel required to fulfill 100% of the human caloric requirements via lignocellulosic sugar production. Values are presented from top to bottom in order of appearance throughout the estimation.

Variable	**Value**	**Unit**	**Notes**

Sugar required to fulfill 100% of human caloric requirements	1.70	Gt/year	Calculated
Dry biomass to sugar mass conversion ratio	36%	-	(Moncada et al., 2018)
Tree mass required to fulfill 100% of the annual human caloric requirement via lignocellulosic sugar	4.73	Gt (dry)	Calculated
Global wet tree biomass volume removed from forests (total roundwood removals)	4	Billion m3	(FAO, 2021)
Expected average tree density	500	kg/m3	(Engineering ToolBox, 2004)
Global wet tree biomass weight removed from forests	2	Gt	Calculated
Expected water content of wet tree biomass	50%		(West, 2004)
Global dry tree biomass weight removed from forests	1	Gt	Calculated
Share of lignocellulosic biomass requirement covered by global tree biomass removals	21%		Result
Global annual production of agricultural residues (dry)	3.5	Gt	(Tieman et al., to be published)
Share of lignocellulosic biomass requirement covered by global agricultural residue production	74%		Result
Global plant biomass	450	Gt C	(Bar-On et al., 2018)
Share of carbon mass in dry biomass	50%		(Bar-On et al., 2018)
Estimated plant dry biomass	900	Gt	Calculated
Share of global plant biomass required to fulfill 100% of the annual global caloric requirements via lignocellulosic sugar	0.5%		Result
Wood harvesting and transport expected fuel consumption	2.5	L/m3	(Ghaffariyan et al., 2018)
Wood chipping expected fuel consumption	0.5	L/m3	(Cadei et al., 2020)

Global liquid fuel production	100	million barrels per day	(EIA, 2021)
Share of global fuel consumption required to process enough biomass to fulfill 100% of global caloric requirements via lignocellulosic sugar	1.0%		Result

References

ACEA, 1950. Freedom's arsenal: the story of the Automotive council for war production. Automobile Manufacturers Association, Detroit, Mich.
ALLFED, 2017. ALLFED [WWW Document]. ALLFED. URL https://allfed.info/ (accessed 7.30.20).
Alvarado, K.A., Mill, A., Pearce, J.M., Vocaet, A., Denkenberger, D., 2020. Scaling of greenhouse crop production in low sunlight scenarios. Sci. Total Environ. 707, 136012. https://doi.org/10.1016/j.scitotenv.2019.136012
Anheuser-Busch, 2018. Jacksonville, FL brewery [WWW Document]. URL https://web.archive.org/web/20181016053422/https://www.anheuser-busch.com/about/breweries-and-tours/jacksonville-fl.html (accessed 5.25.21).
Bailey, R., Benton, T.G., Challinor, A., Elliott, J., Gustafson, D., Hiller, B., Jones, A., Kent, C., Lewis, K., Meacham, T., Rivington, M., Tiffin, R., Wuebbles, D.J., 2015. Extreme weather and resilience of the global food system: Final Project Report from the UK-US Taskforce on Extreme Weather and Global Food System Resilience. UK Glob. Food Secur. Programme. https://www.stat.berkeley.edu/~aldous/157/Papers/extreme_weather_resilience.pdf
Bar-On, Y.M., Phillips, R., Milo, R., 2018. The biomass distribution on Earth. Proc. Natl. Acad. Sci. 115, 6506–6511. https://doi.org/10.1073/pnas.1711842115
Barrett, A.M., Baum, S.D., Hostetler, K.R., 2013. Analyzing and reducing the risks of inadvertent nuclear war between the United States and Russia. Sci Glob. Secur 21, 106–133.
Baum, S.D., Denkenberger, D.C., Pearce, J.M., Robock, A., Winkler, R., 2015. Resilience to global food supply catastrophes. Environ. Syst. Decis. 35, 301–313. https://doi.org/10.1007/s10669-015-9549-2
Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., Woetzel, J., 2019. Modular construction: From projects to products | McKinsey. McKinsey.
Betti, F., Heinzmann, T., 2020. COVID-19: How companies are changing track to join the fight [WWW Document]. World Econ. Forum. URL https://www.weforum.org/agenda/2020/03/from-perfume-to-hand-sanitiser-tvs-to-face-masks-how-companies-are-changing-track-to-fight-covid-19/ (accessed 5.27.20).
Binod, P., Janu, K.U., Sindhu, R., Pandey, A., 2011. Chapter 10 - Hydrolysis of Lignocellulosic Biomass for Bioethanol Production, in: Pandey, A., Larroche, C., Ricke, S.C., Dussap, C.-G., Gnansounou, E. (Eds.), Biofuels. Academic Press, Amsterdam, pp. 229–250. https://doi.org/10.1016/B978-0-12-385099-7.00010-3
Bostrom, N., 2013. Existential Risk Prevention as Global Priority. Glob. Policy 4, 15–31. https://doi.org/10.1111/1758-5899.12002
Branco, R.H.R., Serafim, L.S., Xavier, A.M.R.B., 2019. Second Generation Bioethanol Production: On the Use of Pulp and Paper Industry Wastes as Feedstock. Fermentation 5, 4. https://doi.org/10.3390/fermentation5010004
Brand, K., Donnelly, E., Kaplan, J., Wang, M., You, F., 2014. Sugar Cane Ethanol Plant [WWW Document]. URL https://processdesign.mccormick.northwestern.edu/index.php?title=Sugar_Cane_Ethanol_Plant&printable=yes (accessed 5.24.21).
Cadei, A., Marchi, L., Mologni, O., Cavalli, R., Grigolato, S., 2020. Evaluation of wood chipping efficiency through long-term monitoring. https://doi.org/10.3390/IECF2020-08078
Carter, R.C., 2017. A Reasonable Method to Estimate Loss of Labor Productivity Due to Overtime. Long Int. https://www.experts.com/articles/reasonable-method-estimate-loss-labor-productivity-due-overtime-by-long-international-inc
CEPI, 2017. KEY STATISTICS 2017 European pulp & paper industry [WWW Document]. Confed. Eur.

Pap. Ind. URL https://www.cepi.org/key-statistics-report-2017/ (accessed 5.17.21).
Conway, J., 2018. Global Beer Industry - Statistics & Facts [WWW Document]. Statista. URL https://www.statista.com/topics/1654/beer-production-and-distribution/ (accessed 5.17.21).
Coupe, J., Bardeen, C.G., Robock, A., Toon, O.B., 2019. Nuclear Winter Responses to Nuclear War Between the United States and Russia in the Whole Atmosphere Community Climate Model Version 4 and the Goddard Institute for Space Studies ModelE. J. Geophys. Res. Atmospheres 124, 8522–8543. https://doi.org/10.1029/2019JD030509
Damodaran, A., 2020. Global Capital Expenditures, Acquisitions and R&D and Sales/Invested Capital Ratios [WWW Document]. URL http://www.stern.nyu.edu/~adamodar/pc/datasets/capexGlobal.xls (accessed 9.3.20).
Denkenberger, D., Pearce, J., Taylor, A.R., Black, R., 2019. Food without sun: price and life-saving potential. Foresight 21, 118–129. https://doi.org/10.1108/FS-04-2018-0041
Denkenberger, D.C., Cole, D.D., Abdelkhaliq, M., Griswold, M., Hundley, A.B., Pearce, J.M., 2017. Feeding everyone if the sun is obscured and industry is disabled. Int. J. Disaster Risk Reduct. 21, 284–290. https://doi.org/10.1016/j.ijdrr.2016.12.018
Denkenberger, D.C., Pearce, J.M., 2018a. A National Pragmatic Safety Limit for Nuclear Weapon Quantities. Safety 4, 25. https://doi.org/10.3390/safety4020025
Denkenberger, D.C., Pearce, J.M., 2018b. Micronutrient Availability in Alternative Foods During Agricultural Catastrophes. Agriculture 8, 169. https://doi.org/10.3390/agriculture8110169
Denkenberger, D.C., Pearce, J.M., 2016. Cost-Effectiveness of Interventions for Alternate Food to Address Agricultural Catastrophes Globally. Int. J. Disaster Risk Sci. 7, 205–215. https://doi.org/10.1007/s13753-016-0097-2
Denkenberger, D.C., Pearce, J.M., 2015. Feeding everyone: Solving the food crisis in event of global catastrophes that kill crops or obscure the sun. Futures, Confronting Future Catastrophic Threats To Humanity 72, 57–68. https://doi.org/10.1016/j.futures.2014.11.008
Denkenberger, D.C., Pearce, J.M., 2014. Feeding Everyone No Matter What: Managing Food Security After Global Catastrophe. Academic Press.
EIA, 2021. Short-Term Energy Outlook [WWW Document]. US Energy Inf. Adm. EIA. URL https://www.eia.gov/outlooks/steo/report/global_oil.php (accessed 6.30.21).
El-Mansi, E.M.T., Nielsen, J., Mousdale, D., Carlson, R.P., 2018. Fermentation microbiology and biotechnology, 4th ed. CRC press.
Engineering ToolBox, 2004. Density of Various Wood Species [WWW Document]. URL https://www.engineeringtoolbox.com/wood-density-d_40.html (accessed 6.29.21).
FAO, 2021. FAOSTAT [WWW Document]. URL http://www.fao.org/faostat/en/#data/FO/visualize (accessed 6.29.21).
Fawcett, R., Allison, K., Corner, D., 2005. Using modern methods of construction to build homes more quickly and efficiently. National Audit Office.
Fist, T., Adesanya, A.A., Denkenberger, D., Pearce, J.M., 2021. Global distribution of forest classes and leaf biomass for use as alternative foods to minimize malnutrition. World Food Policy. https://doi.org/10.1002/wfp2.12030
Fornell, R., 2012. Process integration studies on Kraft pulp-mill-based biorefineries producing ethanol. Chalmers University of Technology.
García Martínez, J.B., Alvarado, K.A., Christodoulou, X., Denkenberger, D.C., 2021a. Chemical synthesis of food from CO2 for space missions and food resilience. J. CO2 Util. 53. https://doi.org/10.1016/j.jcou.2021.101726
García Martínez, J.B., Alvarado, K.A., Denkenberger, D.C., 2021b. Synthetic fat from petroleum as a resilient food for global catastrophes: preliminary techno-economic assessment and technology roadmap. Chem. Eng. Res. Des. https://doi.org/10.1016/j.cherd.2021.10.017
García Martínez, J.B., Brown, M.M., Christodoulou, X., Alvarado, K.A., Denkenberger, D.C., 2021c.

Potential of microbial electrosynthesis for contributing to food production using CO2 during global agriculture-inhibiting disasters. Clean. Eng. Technol. 4. https://doi.org/10.1016/j.clet.2021.100139
García Martínez, J.B., Egbejimba, J., Throup, J., Matassa, S., Pearce, J.M., Denkenberger, D.C., 2021d. Potential of microbial protein from hydrogen for preventing mass starvation in catastrophic scenarios. Sustain. Prod. Consum. 25, 234–247. https://doi.org/10.1016/j.spc.2020.08.011
García Martínez, J.B., Pearce, J.M., Throup, J., Cates, J., Denkenberger, D.C., 2020. Methane Single Cell Protein: securing protein supply during global food catastrophes. https://doi.org/10.31219/osf.io/94mkg
Gaupp, F., Hall, J., Hochrainer-Stigler, S., Dadson, S., 2020. Changing risks of simultaneous global breadbasket failure. Nat. Clim. Change 10, 54–57. https://doi.org/10.1038/s41558-019-0600-z
Ghaffariyan, M.R., Apolit, R., Kuehmaier, M., 2018. A Short Review of Fuel Consumption Rates of Whole Tree and Cut-To-Length Timber Harvesting Methods. Curr. Investig. Agric. Curr. Res. 5, 1–3. https://doi.org/10.32474/CIACR.2018.05.000209
Gichuhi, F., 2013. PERCENTAGE OF COST BREAKDOWN BETWEEN LABOUR, MATERIALS AND CONTRACTOR PROFIT IN CONSTRUCTION. [WWW Document]. A4architect.com. URL https://www.a4architect.com/2013/04/percentage-of-cost-breakdown-between-labour-materials-and-contractor-profit-in-construction/ (accessed 6.27.19).
Gonzalez, R.W., Treasure, T., Phillips, R.B., Jameel, H., Saloni, D., 2011. Economics of cellulosic ethanol production: Green liquor pretreatment for softwood and hardwood, greenfield and repurpose scenarios. BioResources 6, 2551–2567.
Grotewold, E., Jones Prather, K.L., Peters, K., 2015. Lignocellulosic Biomass for Advanced Biofuels and Bioproducts: Workshop Report, Washington, DC, June 23-24, 2014 (No. DOE/SC-0170). USDOE Office of Science (SC), Washington, D.C. (United States). Biological and Environmental Research (BER). https://doi.org/10.2172/1471542
GVR, 2020. Biorefinery Market Size, Share & Trends Analysis Report By Product, By Production Technology, Regional Outlook, Competitive Strategies, And Segment Forecasts, 2019 To 2025 (No. Report ID: 97). Grand View Research, Inc.
Hanna, A.S., Chang, C.-K., Lackney, J.A., Sullivan, K.T., 2007. Impact of Overmanning on Mechanical and Sheet Metal Labor Productivity. J. Constr. Eng. Manag. 133, 22–28. https://doi.org/10.1061/(ASCE)0733-9364(2007)133:1(22)
Hanna, A.S., Chang, C.-K., Sullivan, K.T., Lackney, J.A., 2008. Impact of Shift Work on Labor Productivity for Labor Intensive Contractor. J. Constr. Eng. Manag. 134, 197–204. https://doi.org/10.1061/(ASCE)0733-9364(2008)134:3(197)
Hellman, M.E., 2008. Risk analysis of nuclear deterrence. Bent Tau Beta Pi 99, 14.
Huang, H.-J., Ramaswamy, S., Al-Dajani, W.W., Tschirner, U., 2010. Process modeling and analysis of pulp mill-based integrated biorefinery with hemicellulose pre-extraction for ethanol production: A comparative study. Bioresour. Technol. 101, 624–631. https://doi.org/10.1016/j.biortech.2009.07.092
Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B., Worley, M., Sexton, D., Dudgeon, D., 2011. Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover (No. NREL/TP-5100-47764, 1013269). https://doi.org/10.2172/1013269
Ibbs, D.W., Vaughan, C., 2015. Change and the Loss of Productivity in Construction: A Field Guide 94.
Institute of Medicine, 2005. Dietary Reference Intakes for Energy, Carbohydrate, Fiber, Fat, Fatty Acids, Cholesterol, Protein, and Amino Acids. The National Academies Press, Washington,

DC. https://doi.org/10.17226/10490
Janetos, A., Justice, C., Jahn, M., Obersteiner, M., Glauber, J., Mulhern, W., 2017. The risks of multiple breadbasket failures in the 21st century: a science research agenda. The Frederick S. Pardee Center for the Study of the Longer-Range Future.
Kazachkin, D.V., Colakyan, M., Moesler, F.J., 2015. Supercritical hydrolysis of biomass. US9169523B2.
LaJeunesse, S., 2020. Research team to study food resilience in the face of catastrophic global events | Penn State University [WWW Document]. URL https://news.psu.edu/story/622541/2020/06/08/research/research-team-study-food-resilience-face-catastrophic-global-events (accessed 7.30.20).
Larson, E.D., Consonni, S., Katofsky, R.E., Iisa, K., Frederick, J., 2007. Gasification-based biorefining at kraft pulp and paper mills in the United States. Presented at the Proceedings of the 2007 International Chemical Recovery Conference, Quebec City, Canada, Citeseer. http://dx.doi.org/10.32964/TJ8.1.27
Latimer, C.E., Zuckerberg, B., 2019. How extreme is extreme? Demographic approaches inform the occurrence and ecological relevance of extreme events. Ecol. Monogr. 89, e01385. https://doi.org/10.1002/ecm.1385
Lawson, R.M., Ogden, R.G., Bergin, R., 2012. Application of Modular Construction in High-Rise Buildings. J. Archit. Eng. 18, 148–154. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000057
Lee, J.H. (Jay), McCullouch, B., 2009. Review Construction Techniques for Accelerated Construction and Cost Implications (No. FHWA/IN/JTRP-2009/06, 3201). Purdue University, West Lafayette, Indiana. https://doi.org/10.5703/1288284314299
López-Gómez, C., Corsini, L., Leal-Ayala, D., Fokeer, S., 2020. COVID-19 critical supplies: The manufacturing repurposing challenge. U. N. Ind. Dev. Organ. UNIDO. https://www.unido.org/news/covid-19-critical-supplies-manufacturing-repurposing-challenge
Lowey, N., 2020. H.R.6800 - The Heroes Act. https://www.congress.gov/bill/116th-congress/house-bill/6800
Macrotrends, 2021. Sugar Prices - 37 Year Historical Chart [WWW Document]. URL https://www.macrotrends.net/2537/sugar-prices-historical-chart-data (accessed 6.29.21).
Martin, J., Burrows, T.K., Pegg, I., 2006. Predicting Construction Duration of Building Projects. Presented at the Shaping the Change: XXIII FIG Congress, Munich. https://fig.net/resources/proceedings/fig_proceedings/fig2006/papers/ts28/ts28_02_martin_etal_0831.pdf
Martinkus, N., Wolcott, M., 2017. A framework for quantitatively assessing the repurpose potential of existing industrial facilities as a biorefinery. Biofuels Bioprod. Biorefining 11, 295–306. https://doi.org/10.1002/bbb.1742
McAloon, A., Taylor, F., Yee, W., 2000. Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks (No. NREL/TP-580-28893). National Renewable Energy Laboratory.
Merrill, A.L., Watt, B.K., 1955. Energy value of foods: basis and derivation. Human Nutrition Research Branch, Agricultural Research Service, U. S. Department of Agriculture.
Michels, J., 2014. ''Lignocellulose Biorefinery e Phase 2" - Final Scientific and Technical Report of All Project Partners. DECHEMA Ges. Für Chem. Tech. Biotechnol. https://edocs.tib.eu/files/e01fb15/837304261.pdf
Moncada, J., Vural Gursel, I., Huijgen, W.J.J., Dijkstra, J.W., Ramírez, A., 2018. Techno-economic and ex-ante environmental assessment of C6 sugars production from spruce and corn. Comparison of organosolv and wet milling technologies. J. Clean. Prod. 170, 610–624. https://doi.org/10.1016/j.jclepro.2017.09.195
Ou, L., Dou, C., Yu, J.-H., Kim, H., Park, Y.-C., Park, S., Kelley, S., Lee, E.Y., 2021. Techno-economic

analysis of sugar production from lignocellulosic biomass with utilization of hemicellulose and lignin for high-value co-products. Biofuels Bioprod. Biorefining 15, 404–415. https://doi.org/10.1002/bbb.2170
Pearce, J.M., Khaksari, M., Denkenberger, D., 2019. Preliminary Automated Determination of Edibility of Alternative Foods: Non-Targeted Screening for Toxins in Red Maple Leaf Concentrate. Plants Basel Switz. 8. https://doi.org/10.3390/plants8050110
Peters, M.S., Timmerhaus, K.D., West, R.E., 2003. Plant design and economics for chemical engineers, 5th ed. McGraw-Hill New York.
Phillips, R.B., Jameel, H., Chang, H.M., 2013. Integration of pulp and paper technology with bioethanol production. Biotechnol. Biofuels 6, 1–12. https://doi.org/10.1186/1754-6834-6-13
Poduval, A., Ayyagari, M.S., Malinda, M., K.E.K, V., Kumar, A., Kandasamy, J., 2021. Barriers in repurposing an existing manufacturing plant: a total interpretive structural modeling (TISM) approach. Oper. Manag. Res. https://doi.org/10.1007/s12063-021-00209-9
PubChem, 2021. DL-Xylose [WWW Document]. URL https://pubchem.ncbi.nlm.nih.gov/compound/644160 (accessed 6.25.21).
Rein, P.W., 2007. Prospects for the conversion of a sugar mill into a biorefinery. Presented at the Proceedings of the International Society of Sugar Cane Technologists, Durban, South Africa, pp. 44–60. https://sasta.co.za/download/76/14-biorefineries/8891/rein-2007-biorefinery.pdf
RFA, 2019. 2019 ethanol industry outlook [WWW Document]. Renew. Fuels Assoc. URL https://ethanolrfa.org/wp-content/uploads/2019/02/RFA2019Outlook.pdf (accessed 5.17.21).
Richard, A., D'agostino, D., 2016. Methods and compositions for the treatment of cellulosic biomass and products produced thereby. WO2016161515A1.
Robock, A., Oman, L., Stenchikov, G.L., 2007. Nuclear winter revisited with a modern climate model and current nuclear arsenals: Still catastrophic consequences: NUCLEAR WINTER REVISITED. J. Geophys. Res. Atmospheres 112, n/a-n/a. https://doi.org/10.1029/2006JD008235
Seekell, D., Carr, J., Dell'Angelo, J., D'Odorico, P., Fader, M., Gephart, J., Kummu, M., Magliocca, N., Porkka, M., Puma, M., Ratajczak, Z., Rulli, M.C., Suweis, S., Tavoni, A., 2017. Resilience in the global food system. Environ. Res. Lett. 12, 025010. https://doi.org/10.1088/1748-9326/aa5730
Shahbandeh, M., 2020. Sugar consumption by country [WWW Document]. Statista. URL https://www.statista.com/statistics/496002/sugar-consumption-worldwide/ (accessed 5.17.21).
Sinnott, R.K., 2005. Coulson & Richardson's chemical engineering. Vol. 6. Elsevier Butterworth-Heinemann, Oxford.
Souza Filho, P.F., Andersson, D., Ferreira, J.A., Taherzadeh, M.J., 2019. Mycoprotein: environmental impact and health aspects. World J. Microbiol. Biotechnol. 35, 147. https://doi.org/10.1007/s11274-019-2723-9
Sullivan, A., 2019. What Percentage of Construction Costs Is Labor? Pricing Your Bids Correctly [WWW Document]. URL https://www.botkeeper.com/blog/construction-labor-cost-percent (accessed 6.29.21).
Susmozas, A., Martín-Sampedro, R., Ibarra, D., Eugenio, M.E., Iglesias, R., Manzanares, P., Moreno, A.D., 2020. Process Strategies for the Transition of 1G to Advanced Bioethanol Production. Processes 8, 1310. https://doi.org/10.3390/pr8101310
Tao, L., Davis, R., 2017. NREL 2017 Biochemical Sugar Model [WWW Document]. URL https://www.nrel.gov/extranet/biorefinery/aspen-models/index.html (accessed 5.17.21).
TBRC, 2020. Beer Global Market Report 2021: COVID-19 Impact And Recovery To 2030 (No. SKU CODE: r192). The Business Research Company.
Terp, S.-J., Shah, S., Jahn, M., 2020. Earth Day 2020 call for action: Mitigating the global food crises

associated with COVID-19. Atl. Counc. URL https://www.atlanticcouncil.org/blogs/geotech-cues/mitigating-the-impacts-of-global-food-crises-associated-with-covid-19/ (accessed 5.17.21).
Tiseo, I., 2021. Market size of paper and pulp industry worldwide 2019-2027 [WWW Document]. Statista. URL https://www.statista.com/statistics/1073451/global-market-value-pulp-and-paper/ (accessed 6.8.21).
Turner, V.B., 1918. Women in industry. Mon. Labor Rev. 7, 206–233. https://www.jstor.org/stable/41827308
Tzachor, A., Richards, C.E., Holt, L., 2021. Future foods for risk-resilient diets. Nat. Food 2, 326–329. https://doi.org/10.1038/s43016-021-00269-x
U.S. DOE, 2016. Cellulosic Sugar and Lignin Production Capabilities RFI Responses [WWW Document]. Energy.gov. URL https://www.energy.gov/eere/bioenergy/cellulosic-sugar-and-lignin-production-capabilities-rfi-responses (accessed 5.17.21).
USDA, 2012. Alternative Fuels Data Center: Renewable Fuel Standard [WWW Document]. URL https://afdc.energy.gov/laws/RFS.html (accessed 6.3.21).
Van der Meer, T., Fielden, P., Karrenbeld, M., Morgan, T., Christie, E., Riddick, B., 2017. Industrial Capital Expenditure Survey 2017 [WWW Document]. ARCADIS. URL https://www.arcadis.com/-/media/project/arcadiscom/com/perspectives/global/2017/investing-and-building-in-changing-manufacturing-assets/industrial-capital-expenditure-survey-2017.pdf (accessed 5.17.21).
Warner, M., 2019. Industrial Biotechnology Commercialization Handbook: How to Make Proteins Without Animals and Fuels Or Chemicals Without Crude Oil. Independently Published.
West, P.W., 2004. Tree Biomass, in: West, P.W. (Ed.), Tree and Forest Measurement. Springer, Berlin, Heidelberg, pp. 57–68. https://doi.org/10.1007/978-3-662-05436-9_7
WHO, 2004. Food and nutrition needs in emergencies, World Health Organization. https://www.unhcr.org/uk/45fa745b2.pdf