Carbon and energy footprinting across archetypes for U.S. maple syrup production

By

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Abstract

The production of maple syrup from sap requires extensive processing, which has traditionally led to significant energy inputs and greenhouse gas (GHG) emissions per gallon produced. Technology advancements, e.g., vacuum tubing sap collection systems, reverse osmosis (RO), and electric evaporators have changed the way syrup is produced, resulting in widespread variability in processing equipment and sugar-making operational decisions. This paper evaluates these complex operations through a cradle-to-retail gate carbon footprinting model and by capturing variability in a series of producer archetypes. By isolating energy and emissions impacts, we find that implementing RO has the largest reduction effect on energy (54-77%) and emissions (57-82%), depending on both production size and evaporator fuel (wood, fuel-oil, or electricity). Results also demonstrate the effect of production scale on cumulative energy demand (CED) and emissions per gallon of syrup, with small producers ranging from 333-1,425 MJ and 27-118 kg CO_2e/gal (61-90% biogenic on-site) for wood-fired operations and 18-65 kg CO_2e/gal for oil-fired operations. Large producers ranged from 90-131 MJ and 3.5-7 kg CO_2e/gal (electricity to oil-fired operations). Producers of all scales with the highest rates of electrification in their operations have the lowest GHG emissions and energy use per gallon of syrup produced.

Keywords: Maple Syrup, Food Systems, GHG Emissions, Energy, LCI

Synopsis: Archetypes for characterizing 10,000 U.S. maple syrup producers are created to evaluate process carbon footprints and provide guidance on decarbonization strategies.

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Contents

Preface

The bulk of the work included in this thesis integrates a comprehensive modeling effort of the United States maple syrup industry and producer data from across the maple producing region to quantify the carbon footprint of US made syrup. This thesis is currently under final review for publication in Environmental Science & Technology (ES&T). Beyond this paper, two reports authored by me and published through the Center for Sustainable Systems (CSS), are included as appendices B and C. These reports outline the thermodynamic and fluid mechanics models developed to create the archetypes that were fed into the life cycle analysis (LCA) model which is outlined in the first chapter.

At the time of submission of this thesis, the modeling effort highlighted is also being used to conduct an economic analysis of the cost of carbon abatement of specific technological decisions in variable climate scenarios. This thesis serves as the backbone for this model and utilizes the same methods described in appendices A-C. The economic analysis phase of the project is currently being prepared into a manuscript for publication. The economic model incorporates the upfront cost of capital, annualized fixed and variable costs, the weighted average costs of capital (WACC), and total production to calculate the levelized cost of maple syrup (LCOM) for each archetype. The levelized costs are compared across the archetypes used in this thesis, as well as compared across future cost and climate scenarios. The scenarios included in the economic model factor in seasonal variations in sap sugar concentration and sap flow to generate production, revenue, and total carbon. Regional and temporal variations with respect to fuel and distribution costs were also considered for 2024 as well as 2050.

Introduction

In 2021, the agricultural sector was responsible for 11% of total CO_2 emissions in the United States.[1] In order to avoid the most drastic impacts of climate change, the IPCC has set a goal of reducing emissions 45% by 2030 relative to 2010.[2] Achieving this target will take large-scale decarbonization across all economic sectors. Within the agricultural sector, maple syrup producers are becoming increasingly concerned with the carbon footprint of syrup production, and the International Maple Syrup Institute (IMSI) as well as industry leaders have recently listed it as one of their top research priorities.[3] While energy efficiency improvements by producers are motivated by cost and time savings,[4] there is uncertainty about which production practices have the greatest impact on greenhouse gas emissions (GHG).

Maple sap requires energy-intensive concentration to produce finished syrup.[5] A common rule of thumb is that it requires 40 gallons of sap to make 1 gallon of syrup. This is true if the sap sugar content is 2.1 degrees Brix (°Bx) (1°Bx indicates a 1% sucrose solution by volume), but according to the *Revised Jones Rule*, it can take anywhere from 30 gallons of 2.9°Bx sap to over 70 gallons of 1.2°Bx sap.[6] There are many factors that determine the sugar content and yield of maple sap, with climate change having the potential to impact interannual (e.g. winter snowpack, mean seasonal temperature, and growing degree days)[7–15] and site-specific effects (e.g. soil composition, tree health, species competition).[12,16,17]

The technology employed to concentrate sap to syrup has improved markedly. Time and energy required to produce syrup is only a fraction of what it was decades ago. Membrane concentration, commonly referred to as reverse osmosis (RO), systems and more efficient evaporators greatly reduce the time and fuel needed to bring raw sap to 66°Bx syrup. Some sugarmakers forgo the use of RO because they believe it has a negative impact on the flavor of finished syrup or so they can market their syrup as being made with traditional methods, though studies have shown that RO has no discernible effect on maple syrup flavor.[18–20] For producers who utilize RO, some will only take the sap up to 4°Bx before boiling because they want to boil it long enough to create 'traditional' maple flavor. Other producers bring their sap sugar content as high as 35°Bx with RO to minimize the amount of time and fuel spent running an evaporator. A recent study suggests that pre-concentration to this level can reduce the energy costs of maple syrup production by 85% compared to evaporation alone.[21] They built on previous more general work on the energy requirements for removing water from sugar solutions by Madaeni and Zereshki.[22]

The most common way syrup is made at scale is by boiling in an evaporator, because it saves time, decreases overall fuel costs, and produces a higher quality product.[23] Fuels used in evaporators include fuel oil, propane, natural gas, cordwood, wood chips, wood pellets, steam, and electricity. Evaporator size and design impact fuel efficiency, as preheaters, heat recovery, forced air, and other features greatly impact the amount of water evaporated per unit of fuel input. Emissions impacts associated with electricity use (for RO, pumps, and evaporators, for example) vary with the regional mix of generation fuels used– hydropower results in minimal GHG emissions per kWh while coal results in large emissions.

While there is great variation in syrup processing, especially among smaller producers, there is also potential for variation in energy consumption and solid waste generation from sap collection and transport. Producers have the choice of using reusable buckets (plastic or stainless) or plastic bags to collect sap, then collecting and transporting it to the sugarhouse by horse, tractor, ATV, or truck. Tubing is commonly used for sap collection for all scales of operation, especially in larger stands (>10,000 taps) where bucket collection becomes inefficient. The environmental impact (energy inputs, emissions outputs, and solid waste produced) of the collection process varies depending on whether sap flows by gravity (either in buckets or tubing) or by use of a vacuum pump on a tubing system, as well as whether the tubing leads directly to the sugarhouse or the sap needs to be transported by vehicle. Tubing system lifespan and how often different components (e.g., spouts, drop lines, lateral lines) are replaced also impacts waste generation and the syrup's carbon footprint.

Life cycle assessment (LCA) is a systematic accounting method based on a standardized framework and terminology that is used to quantify the effects on the environment from the products and services that meet human needs.[24] LCA involves compiling and evaluating the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle. This life cycle perspective includes the burdens of acquiring and producing energy (e.g., electricity, fuels) and material inputs (e.g., steel, plastic) as well as manufacturing, use, and disposal of a product. LCAs provide information necessary for carbon accounting efforts, labeling/certification programs (e.g., USDA organic, Ecocert Climate Neutral), and guiding burden reduction strategies as well as providing a framework to separately account for biogenic and fossil carbon.

Many US food industry groups, including dairy,[25] beef,[26] pork,[27] poultry,[28] and almonds[29] have conducted LCAs of their products. Such studies are invaluable to these industries not only for outreach and communication purposes but also to guide improvements. No comprehensive life cycle assessment of maple syrup production has been published, but maple producers have addressed individual environmental issues, such as avoiding lead contamination.[30] Fully evaluating GHG and solid waste impacts of maple syrup production with LCA is a necessary first step towards understanding which process stages are responsible for the greatest burdens and to help guide their reduction. The industry has begun addressing agricultural plastic waste in Quebec by establishing the environmental handling fee (EHF), which supports the recycling of maple tubing through an upfront payment upon purchase.[3,31–33] A general strategy for emissions reduction is to electrify the equipment used and decarbonize the grid. This strategy also applies only to those with access to both low-carbon electricity supply and capital to upgrade equipment.

This paper describes the development and application of a comprehensive life cycle model for maple syrup production that captures starting sap sugar content, varying processing methods and fuels, production scales (in three categories by number of taps), and variation in electricity emissions across the 13 maple syrup-producing U.S. states in the North American Maple Syrup Council (NAMSC). We have advanced LCA methods by constructing a set of archetypes that classify the variability among the nearly 9,600 maple syrup producers in the U.S. and isolate the burdens of individual process steps in order to capture the complexity inherent in maple syrup production processes.[34] While 95% of syrup produced in 2022 came from producers classified as medium (1,000-10,000 taps) or large (>10,000 taps), these operations were only 27% of all reported operations.[35,36] By constructing archetypes for small, medium, and large producers, this approach allows us to make specific recommendations regarding emissions reductions actions across scales of production. This approach is applicable beyond the maple syrup industry into other agricultural products where widespread variability across scales is present in production, e.g., dairy, coffee, poultry, or honey.

Methods

This study examines the stages of maple syrup production from cradle to retail gate, including sugarbush maintenance and management, sap collection, sap processing and boiling, and on-site bottling, as illustrated in the process model diagram in Figure 1. Sugaring operations vary widely in production scale, production methods, geography, and physical conditions of the individual sugarbush, all of which affect the environmental impact of the syrup-making process. To understand how each of these factors influences the environmental footprint, cumulative energy demand (CED), global warming potential (GWP), and solid waste were chosen as impact categories. GHG emissions are reported separately for fossil, biogenic, and electricity sources. Water use was not analyzed due to a lack of producer water consumption data.

Figure 1 illustrates the different fuels and materials associated with each process stage. To isolate the contribution of each production practice, we constructed a set of archetypal syrup production operations (defined in Table 1) to reflect most common practices within the industry.

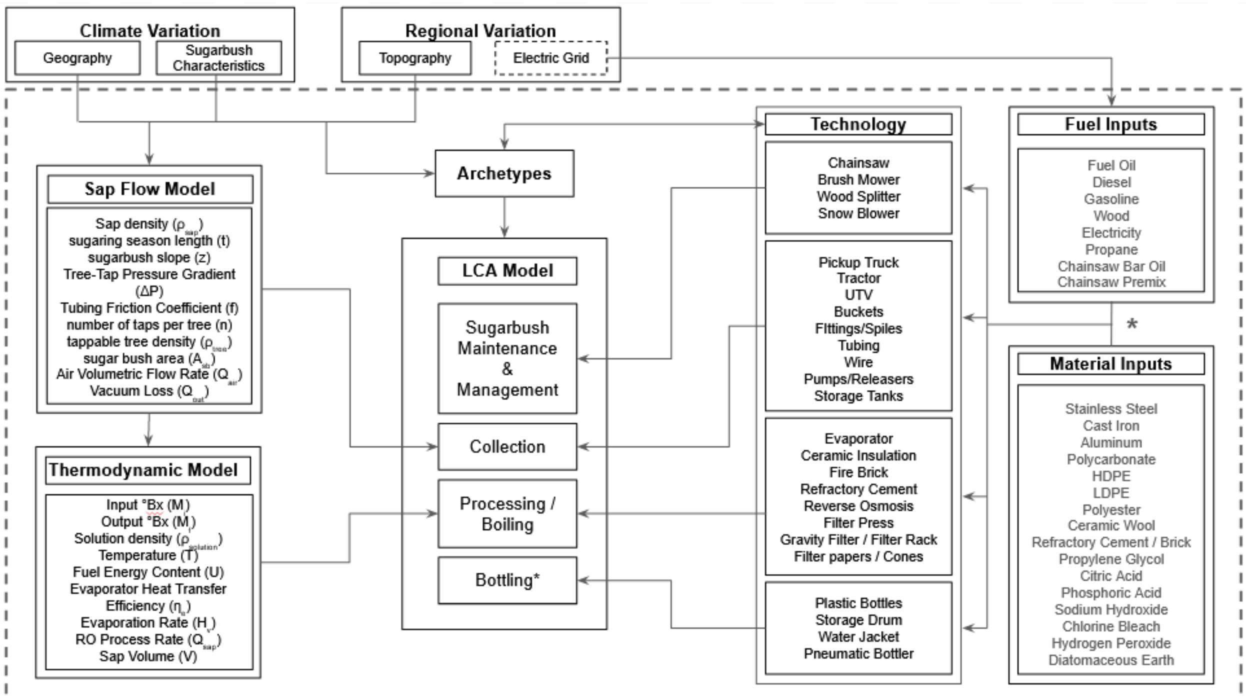


*Figure 1 Sap to syrup process model block diagram - process stages are outlined in bold, dashed line is the system boundary for this analysis. *For specific production steps involved in fuel and material inputs refer to Figure S1.*

These archetypes are informed by producer data and industry knowledge across three operational scales (as quantified by number of taps) representing the likely bounds within which technological decisions can be made: small (<1,000 taps); medium (1,000-10,000 taps); and large (>10,000 taps). We assume that decisions would be made only in the direction of improving operational efficiency so that a small operator might add RO to decrease boiling times, but a large operator won't switch from tubing to buckets for sap collection, as this would increase both time and labor costs associated with collection. Following sections describe assumptions and modeling inclusions.

Table 1 Process model archetype definitions (base case archetypes are S0, M0, and L0). All archetypes assume the same 2 °Bx sap sugar content. RO output is 8 °Bx for S archetypes, 12 °Bx for M1, M2, M3, 15 °Bx for L0 and 30 °Bx for M4 and L1.

	size	**#taps**	**collection**	**vacuum**	**filter press**	**RO**	**evaporator fuel**	**heat recovery**	**bottle on-site**	**retail**
S0	small	<1,000	bag / bucket	no	no	no	wood/oil	no	yes	local/ non-local
S1			bag / bucket	no	yes	no	wood/oil	no		
S2			tubing	no	yes	no	wood/oil	no		
S3			tubing	yes	yes	no	wood/oil	no		
S4			tubing	yes	yes	yes	wood/oil	no		
S5			tubing	yes	yes	yes	wood/oil	yes		
M0	medium	1,000-10,000	tubing	no	yes	no	wood/oil	some	yes	local/

										non-local
M1			tubing	no	yes	yes	wood/oil	some		
M2			tubing	yes	yes	yes	wood/oil	some		
M3			tubing	yes	yes	yes	wood/oil	yes		
M4*			tubing	yes	yes	yes	electric	yes		
L0	large	>10,000	tubing	yes	yes	yes	oil	yes	yes	local/ non-local
L1*			tubing	yes	yes	yes	electric	yes		

*emissions impacts vary by geography for these archetypes based on differences in electricity grid emissions factors.

Data Description

We modeled vehicle production and use burdens using data from Argonne National Lab's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.[37] Stationary and mobile combustion emissions were estimated using a combination of GREET and US EPA combustion accounting guidelines.[1,38–40] US EPA provides energy and emissions data at the point of combustion and GREET provides data on upstream energy and emissions. For cars and trucks, GREET provides data across the total vehicle life cycle and fuel cycle (upstream and combustion). We tabulate CO_2, N_2O, CH_4, and total GHG emissions in kg CO_2e/mile (using AR6 GWP 100 emissions factors), and total primary energy (HHV) (in MJ/mile) from these data. Modeled vehicle types include farm vehicles, personal vehicles (LDVs), and trucks (HDVs). Electric vehicles are also included so that differences in energy and emissions burdens between them and conventional fuel vehicles can be evaluated. Impacts from electricity use by state are sourced from GREET.

Data on sap and syrup processing equipment (materials and weights, energy use, lifetime) were sourced from manufacturers and distributors (refer to Appendix A page 25 for references on model construction). Material production data for sap collection and processing equipment were sourced from GREET. Material production impacts for all equipment were allocated based on use during the season with respect to the equipment's design lifetime. Data on cleaners, defoaming agents, and agricultural inputs came from GREET, SimaPro,[41] and previous LCA[42–45] work conducted for these products.

Sugarbush Maintenance & Management

Life Cycle Model

Sugarbush maintenance and management constitutes tasks performed on the sugarbush itself. Examples include firewood collection, tree thinning, brush clearing, and, albeit rare in the current state of the industry, fertilization. This work could occur at any time, including in the offseason.

Archetype Construction

Off-season activities are assumed to vary linearly with production scale, as sugarbush maintenance only relies on acreage and number of trees. More land area implies more energy, labor, and equipment are required for those activities.

Collection

Life Cycle Model

Sap collection methods vary widely among producers, with some using buckets or collection bags at each tap, and others using tubing systems to collect sap at one or more locations. For those with tubing systems, choosing to add a vacuum pump enhances productivity and sap yields at the cost of additional electricity demand. Equipment used in this stage includes vacuum pumps and releasers, process pumps, extractors, and vehicles for both the collection and transportation of sap to the sugarhouse. Production impacts for tubing, taps, fittings, wire, saddles, buckets, collection bags, and storage tanks are accounted for in this stage.

Archetype Construction

The archetypes in Table 1 drive decision making for different collection methods. We assume that most medium and large producers have moved away from buckets in favor of a tubing collection system,[46] though vacuum use remains variable for medium producers. Producers with steep slopes (8-15%) in their sugarbush may be able to leverage gravity to produce vacuum in a 3/16" tubing system without a pump.[47] We conservatively estimate average slope to be 2%.[48] For scenarios including vacuum, we selected a pump rated for the sugarbush size (based on number of taps) from the Becker Maple Extraction Catalog.[49] The main-line tubing system was then designed to optimize the amount of vacuum at the tap (25" Hg) while accounting for system leakage and frictional losses.[50,51]

Processing & Boiling

Life Cycle Model

Processing and boiling includes all activities for turning sap into syrup from when it enters the sugarhouse, through the RO, evaporator, and filter. For those using RO, energy for space heating is also required, as RO units need to be kept above freezing.[52] Production burdens from filter papers, cones, and filter tanks are also included. This stage is the primary source of variability in fuel use, as evaporators utilize different fuel types and operate at varying efficiencies based on their construction. Fuel impacts are calculated for the total fuel cycle (upstream and use).

Archetype Construction

Best practices for fuel type and technology are a subject of debate within the maple community. The number of economically viable options in both categories decreases as production scale increases. For example, wood fuel leads to increased labor and time spent boiling due to lower evaporator efficiency, and time required to boil sap from a large sugarbush would be considerably shortened by using RO. The archetypes in Table 1 represent the variability in practice (specifically in this stage), while also considering constraints on time, labor, and capital. Constructing the archetypes required quantifying the productivity changes that would arise from the different set-ups. Building on the decisions made in the collection scenarios, productivity was calculated for each system (e.g., buckets, tubing, tubing with vacuum), with respect to a standardized yield of eight gallons of sap per tap per season at atmospheric pressure.[53–55] Filtering was assumed to be pumped (electric) at all scales, with only the baseline case for small producers using gravity filtration. Matching the boiling rates of the evaporator with the volume of sap processed throughout the season, the number of boiling runs could be calculated based on the length of an average boil.[46] Fuel consumption was calculated by integrating a new thermodynamic model for sap boiling, which assumed a sap sugar content of 2 °Bx, starting temperature of 5 °C, and syrup sugar content of 67 °Bx (details in Appendix A).[56] ROs were sized to match evaporator boiling rates to avoid processing lags and storage before boiling.

Bottling

Life Cycle Model

Bottling impacts depend on the type of operation as well as production scale. Some producers bottle and retail their syrup from their sugarbush or local outlets, others ship syrup in barrels to a packer or a wider network including grocers and restaurants. In the 2022 season, 59% of syrup was sold in bulk.[57] Packers may produce some syrup on their own but buy most of their syrup from local producers for packaging and sale through a retail distribution network.

Equipment modeled for the bottling stage included insulated water jackets, propane heaters, and pneumatic bottling machines. Material production impacts for bottles and barrels were also included. Other post-boiling equipment such as sugar sifters and candy machines are outside the scope of syrup production. Impacts from distribution are compared across different retail distances averaged across the network, with a maximum of 2,000 km. Distribution scenarios, which all assume plastic containers, are based on data from a separate distribution model.[58]

Archetype Construction

For the archetypes we assume that those who bottle onsite have a smaller retail radius than those who retail through a packer. The distribution network can be thought of separately from the production process, as the only distribution variable that changes with scale is the volume of syrup being retailed. Decisions regarding local and non-local distribution can therefore be compared directly for each archetype (see Appendix A for distribution model and impacts).

Results & Discussion

Energy

Figure 2 illustrates cumulative energy demand (CED) per gallon of syrup decreasing as scale increases: 1,425-333 MJ/gal, 1,238-116 MJ/gal, and 131-90 MJ/gal for small, medium, and large producers respectively. This trend also holds as evaporator fuel changes from wood to oil to electricity (1,425-410 MJ/gal to 992-333 MJ/gal for small producers going from wood to oil, 1,238-221 MJ/gal to 809-176 MJ/gal to 116 MJ/gal for medium producers going from wood to oil to electricity, and 131 MJ/gal to 90 MJ/gal for large producers going from oil to electricity). For small and medium producers, the processing stage dominates CED, with boiling sap into syrup being the major contributor. For larger producers, sap collection dominates, as the amount of tubing, vehicle use, and electricity for pumping scale relatively linearly with operation size, while processing becomes comparatively more efficient, lowering its overall share of CED/gal.

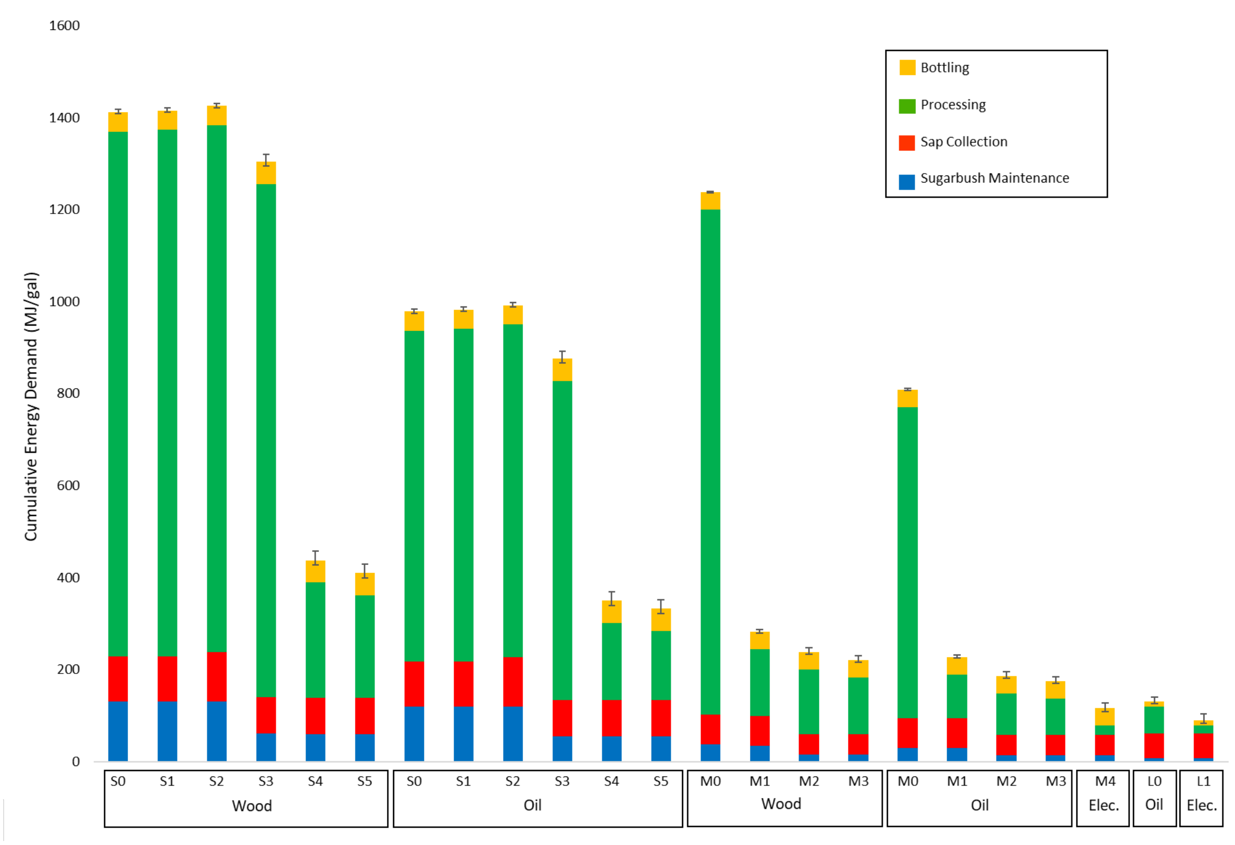


Figure 2 Cumulative Energy Demand (CED) per gallon. Error bars illustrate variability in primary energy demand due to electricity grid mix differences across all process stages. The average (the top of the yellow bars) is

calculated using the 2022 syrup production weighted average primary energy ratio (PER) for electricity across all 13 NAMSC states (2.11). The low end of the error bars is VT (PER 1.66), while the high end is WI (PER 2.93).

The geographic distribution of maple producing regions introduces variability in CED due to differences in electricity mix, as shown by the error bars in Figure 2. Scenarios utilizing RO (S4, S5, M2, M3, M4, L0, L1) have higher variability, as a greater share of the operation is electrified. In all RO scenarios, CED is substantially reduced compared to those not using RO (reductions of 61.4% for small producers using wood fuel, 53.8% small using oil fuel, 77.2% for medium producers using wood fuel, and 71.9% for medium using oil fuel). Sugarbush maintenance has the lowest impact of the four process stages across medium and large scales as well as for small producers that are more efficient in boiling (S3-S5). Sugarbush maintenance is relatively higher in the small wood-fired and oil-fired scenarios (S0, S1, S2) mainly due to small yields doing little to lessen the production burdens on a per gallon basis.

Small producers

For small producers using wood fuel, the reduction in CED if all five production process changes in Table 1 are made (S0→S5) is 71% from baseline case S0, as shown on the left side of Figure 3. Most of the reduction (61% from the baseline) comes from the addition of RO (S3→S4).

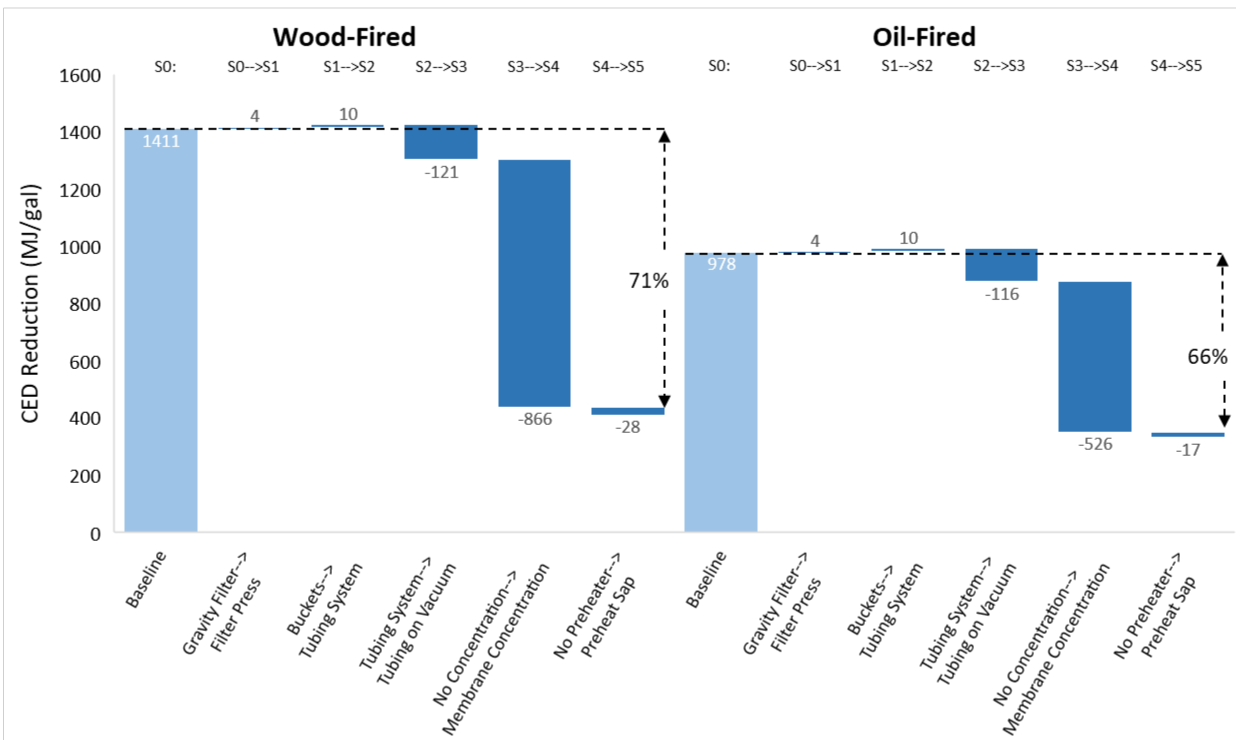


Figure 3 Energy reduction by process change for small producers using wood (left) or fuel oil (right) as the evaporator fuel. CED reductions are with respect to the baseline case (gravity filtering, buckets, no vacuum, no RO, no preheater on the evaporator).

There is a slight increase in CED/gal from a change in filtering (S0→S1), despite more energy going into washing filter cones than operating a filter press. Most new filter presses are made with aluminum plates, which has significantly higher production impacts than stainless steel. The energy increase when changing from buckets to tubing (S1→S2) is a result of a large amount of material production for a tubing system and a lack of displacement of vehicle use. Inefficient vehicles like pickup trucks with trailers and UTVs were modeled as the primary modes of collection, making the overall energy impact of adding a tubing system dependent on how much vehicle use is displaced. Adding vacuum (S2→S3) increases energy use, but also increases the overall sap yield by 119%. The resulting increase in syrup produced reduces the energy input on a per gallon basis compared to the non-vacuum scenarios (by 8.6% from tubing alone). There is a hyperbolic relationship between input °Bx and energy needed to boil, meaning energy increases to concentrate sap with RO (in the small scenarios 2°Bx → 8°Bx) are much smaller than the decrease in energy needed to boil (61.4% decrease). The addition of a preheater (S4→S5) improves the efficiency of the boiling process by ~15%. In this case, boiling efficiency for wood goes from 40% to 46% efficient, leading to an overall reduction in CED/gal of 2%.

For small producers using fuel oil, the same trends apply. The highest energy reduction comes from the implementation of RO, followed by vacuum, preheaters, a filter press, and tubing (see the right side of Figure 3). The total reduction in energy after all five process changes are made is 66%. The oil-fired evaporator being more efficient than a wood-fired evaporator makes each process step proportionally less impactful at reducing the total amount of fuel, demonstrated by the RO and preheater energy reductions being less significant than for a wood-fired producer of the same size. In the case of tubing and vacuum, there is an increase in magnitude for their respective impacts as they are not directly tied to the boiling process (which is more efficient than with wood). As yield increases by adding vacuum, the increase in syrup produced is at a lower per-gallon energy cost to boil due to the higher evaporator efficiency for an oil-fired evaporator.

Medium producers

For medium-sized producers, the absence of buckets means that the sap collection stage for the baseline (M0) is a smaller fraction of the total energy than in the small baseline scenarios (5% vs. 7% for wood-fired and 8% vs. 10% for oil fired). Therefore, all process changes that directly affect boiling time and efficiency have proportionally higher impacts on energy reduction, as shown in Figure S2.

The reduction in CED from implementing all four process changes is 91%. RO has the largest impact (77% reduction). The overall impact is larger here, in part due to the increase in concentrating °Bx (2°Bx → 12°Bx) compared to the smaller producer (2°Bx → 8°Bx). The increase in concentrating °Bx is mainly a function of the amount of sap that needs to be processed, with units that have faster flow rates also concentrating to a higher level. The next largest reduction comes from the implementation of a higher efficiency electric evaporator (working at lower pressures) and steam kettle (to bring it up to boiling). Achieving this efficiency requires a higher input concentration (30° Bx), which significantly reduces energy consumption during boiling. The evaporation rate of the electric evaporator is slightly lower than the 4'x12' wood-fired arch, which leads to a lower processing rate per unit of fuel input.

For oil-fired medium-sized producers, the reduction from implementing all four process changes is 86%, illustrated in Figure S5. The order of lowest-to-highest impact does not change compared to the wood-fired case, with a preheater having the lowest impact (1.3%) followed by a vacuum (5.2%), electric evaporator (7.4%), and RO (72%). The same evaporator efficiency logic applies as in the case of small oil-fired versus small wood-fired producers, where the proportional impact of boiling-related process changes (RO, preheater, electric evaporator) has lower relative impacts in the oil case than in the wood case because the baseline efficiency of the wood-fired case is so low. This means that the non-boiling change (vacuum pumps) is the only one that leads to a higher proportional impact than in the wood-fired case (5.2% vs 3.6%).

Large producers

In the case of a large producer switching from oil-fired to electric evaporators, the total decrease in CED is 31%. The logic is the same as in the medium case (M3→M4), where there is both an increase in the necessary input concentration (15 °Bx → 30 °Bx), as well as an increase in evaporator efficiency (84% for oil w/preheater in L0 versus low pressure electric followed by an electric steam kettle). The process rate of the electric evaporator and steam kettle is lower than the 5'x14' oil-fired arch.

GHG Emissions

GHG emissions are categorized as biogenic (wood), fossil (oil), or electric, where electricity emissions vary with local grid mix and may be partially reduced by on-site renewable energy generation. The only scenarios that have biogenic emissions on-site are the small and medium wood-fired evaporator cases, as shown in Figure 4. There are biogenic emissions that vary by state from 0-25% of the electricity emissions in the maple producing states (multiple states are at 0%, with ME at 25%). For small producers, emissions ranged from 27-118 kg CO_2e/gal (61-90% biogenic on-site) for wood-fired operations and 18-65 kg CO_2e/gal for oil-fired operations. For medium sized producers, the range was 14-105 kg CO_2e/gal (62-93% biogenic on-site) for wood-fired operations, 9-53 kg CO_2e/gal for oil-fired operations, and 4.5 kg CO_2e/gal for electric operations. For large producers, oil-fired operations emitted ~7 kg CO_2e/gal and electric operations emitted 3.5 kg CO_2e/gal. The overall trend in emissions is the same as CED, where emissions intensity in kg CO_2e/gal decreases for both fossil emissions and biogenic carbon as production scale increases. Electricity emissions increase from the baseline of each archetype, while fossil, biogenic, and overall emissions decrease on a per gallon basis. Adding RO decreases the amount of fuel needed for boiling, which substantially reduces combustion emissions.

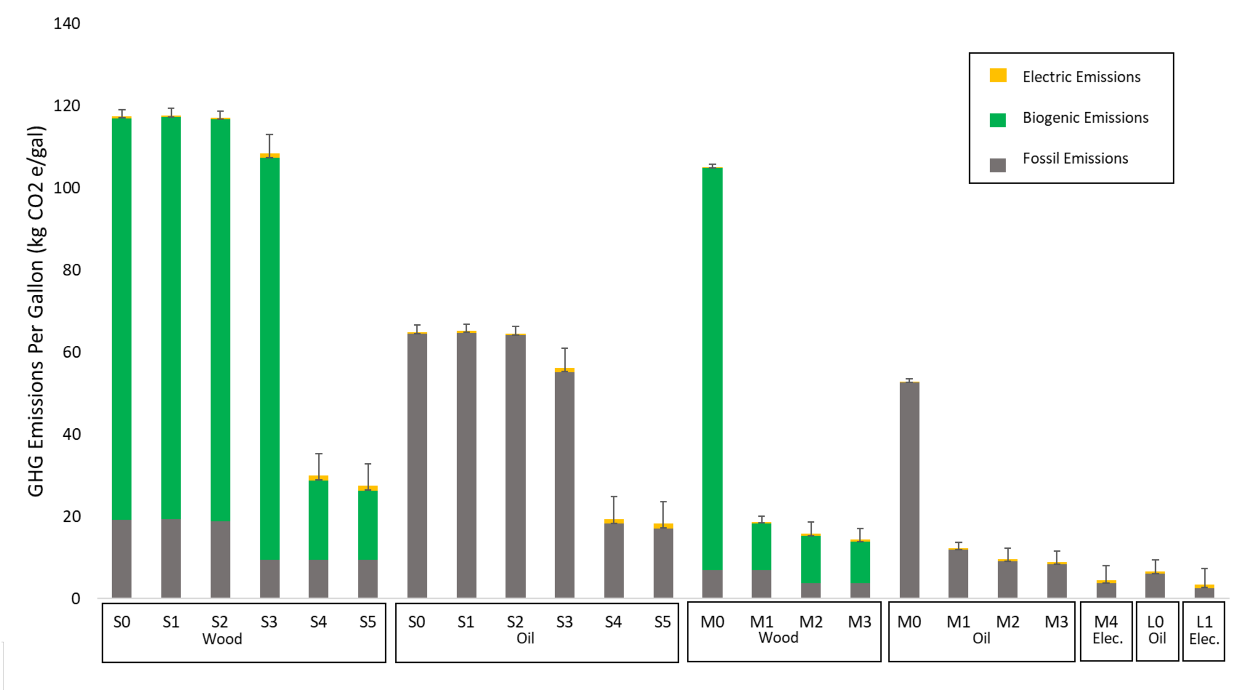


Figure 4 GHG emissions broken down by emissions category: biogenic (wood), fossil (embodied carbon and fossil fuel consumption), and electric (emissions from the grid), for different production scales and fuel types. Error bars represent variability in electricity emissions based on geography, with the average being the 2022 syrup production weighted average of the 13 NAMSC state grids (0.18 kg/kWh), the low being VT (0.02 kg/kWh), and the high being WV (1.02 kg/kWh).

Processing (RO, boiling, and filtering) is the production stage with the largest emissions per gallon, for both wood and oil-fired operations, while sap collection is the largest for electric operations (see Figure S3). This trend is consistent with CED, as processing remains the largest source of overall emissions until the boiling stage gets more efficient, and vehicle use remains a large part of collection.

Small producers

The emissions reduction for a small producer using wood fuel after implementing all five process changes is 77%, as shown in Figure 5. RO results in the greatest emissions reduction (67% from baseline). The increase in electricity emissions (0.7% weighted as a fraction of added GHG emissions with respect to total baseline emissions) is less than the total reduction in biogenic and fossil emissions. The decrease in emissions is directly related to the reduction in boiling fuel consumption. The order of total emissions reduction for the other changes is vacuum (7.4%), preheater (2.2%), tubing (0.5%), and an electric filter press (0.2% increase). The addition of tubing and vacuum pumps both have a greater effect on fossil than on biogenic or electricity emissions. Vacuum pumps increase electricity emissions while also increasing yield, which reduces the relative impact of the tubing system and all non-boiling fossil fuel consumption on a per gallon basis (by removing the need for a transfer pump). Tubing reduces the amount of fossil fuel used in transportation in the sap collection stage. The only source of increased fossil emissions comes from the switch to electric filtering (+0.25 $kgCO_2e/gal$), which stems from the production burdens to manufacture a filter press.

Figure 5 GHG emissions reduction by process change for small producers using wood as the evaporator fuel. Reductions for each emission type (fossil, biogenic, electric) are calculated with respect to the total emissions in the baseline case (gravity filtering, buckets, no vacuum, no RO, no preheater on the evaporator). All assume a 2022 syrup production weighted NAMSC average electric grid (0.18 kg/kWh), with the low end of the range being VT (0.02 and the high being WV (1.02 kg/kWh).

For a small producer using oil fuel, emissions reduction after implementing all five process changes is 72%, as shown in Figure 6. As with the wood-fired case, RO has the highest impact (57%), followed by vacuum (12.9%), a preheater (1.8%), tubing (0.9%), and an electric filter press (0.4% increase). The comparison between fuel oil and wood emissions is the same as the comparison for CED, where the efficiency of the evaporator dictates the amount of fuel used and the overall significance of each process change. The largest reduction for the wood case is biogenic, whereas for oil-fired the largest reduction is fossil emissions. Electricity emissions increase 0.7% with respect to baseline emissions in the wood case and 1.2% in the fuel oil case, as the higher efficiency oil-fired evaporator means less fuel is saved when more parts of the process are electrified.

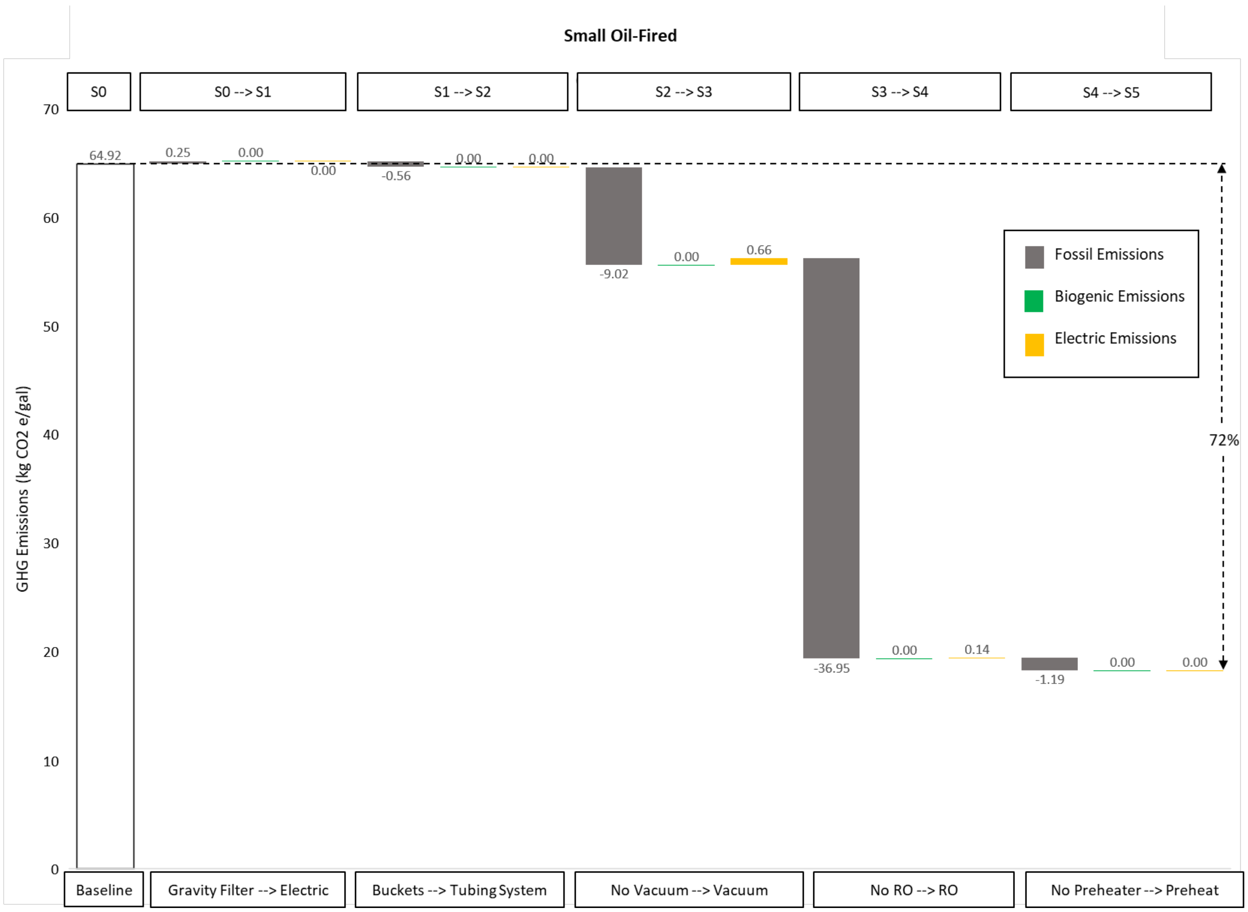


Figure 6 Emissions reduction by process change for small producers using fuel oil as the evaporator fuel. Reductions for each emission type (fossil & electric) are isolated with respect to the baseline case (gravity filtering, buckets, no vacuum, no RO, no preheater on the evaporator). All emissions are represented in a 2022 syrup production weighted average NAMSC electric grid (0.18 kg/kWh).

Medium producers

The overall emissions reduction for wood-fired operations when implementing the four process changes shown in Figure S4 is 96%, the majority of which comes from adding RO (82% from baseline). Medium-sized producers already have efficiency gains from including tubing in the baseline (M0) that were not present in the small producer baseline (S0). Added electricity emissions from RO are small compared to the reduction in emissions during boiling. The next highest impact comes from an electric evaporator, which decreases baseline biogenic emissions from 97.9 to 0 kg CO_2e/gal, contributing to a 93% reduction in total emissions. The only source of increased emissions is electricity, which can potentially be reduced to zero if the electricity is 100% renewable. In the renewable electricity case, medium-sized producers using wood fuel have the potential to decrease emissions by an additional 0.6% from the baseline.

Medium-sized producers using oil-fired evaporators reduce emissions by 91% when all four changes are implemented, as shown in Figure S5. Reductions are in the same order as in the wood case, with all steps related to the reduction in fuel use in the boiling stage being slightly less impactful than for a wood-fueled producer of the same size. There is a greater increase in electricity emissions between baseline M0 and scenario M4 for oil-fired operations as more components become electrified. If all electricity is supplied by renewable sources, the medium oil-fired producer has the potential to decrease emissions by 92.6%. Other than efficiency, the reduction is slightly lower than in the wood-fired case, because when transitioning to an electric evaporator, other capital equipment is removed from the production process for a wood-fired producer (e.g., a wood splitter) that is not removed in the oil-fired case.

Large producers

The emissions reduction for large producers switching from oil-fired to electric evaporators is 48%, which is a combination of an increase in electricity emissions from doubling the input concentration from the RO and using an electric evaporator. In a scenario where all electricity is supplied by renewable sources, the emissions reduction potential is 51.6%.

Solid Waste

Solid waste is a function of the tubing system, packaging, and filter waste, all which scale linearly with operation size and do not depend on evaporator fuel type. The range of solid waste extends from 0.44-1.27 kg/(gal-yr.) (see Tables S16 and S17), which corresponds to a range of embodied carbon of 0.89-2.34 kgCO_2e/(gal-yr.). For small producers, this corresponds to a range of 5-17% of the total fossil carbon for wood-fired producers, and 2-9% of the fossil carbon for oil-fired. For medium sized producers this corresponds to 30-35% of the fossil emissions for wood-fired operations, 4-17% of the fossil emissions for oil-fired, and 36% of fossil emissions for electric. For large producers, it's 15% and 34% of the fossil emissions for oil-fired and electric respectively. Normalizing for syrup produced, the worst performers for solid waste per gallon (S2, M0, M1) are operations that do not utilize vacuum with their collection tubing systems and are therefore less productive. The more syrup produced with the same amount of material input leads to lower impacts on a per gallon basis.

The amount of tubing is dependent on the area of the sugarbush, so operations that are spread over multiple acres produce more total waste. Even as vacuum is added to the system, the increase in tubing and bottles used to package the extra syrup produced leads to somewhat higher waste per gallon from smaller to medium producers. The best-case scenarios are large producers who ship mostly in bulk and the small bucket baseline scenario (S0), where the only solid waste comes from taps, packaging, and filter waste.

Shipping Inflows and Distribution Outflows

For all scenarios, equipment, packaging, and some fuels (like fuel oil) are shipped to the sugarbush. Shipping has less of an emissions impact when the shipping distance is shorter (refer to SI for details). The archetypes with the greatest GHG impact are the oil-fired operations. In these archetypes, the shipment of fuel oil to the sugarhouse represented the largest payload annually. Even in the worst case on a percentage basis (M0 oil, 700 km average shipping inflow distance) the shipment of equipment and fuels to the sugarbush accounts for less than 1.14% of total emissions. Operations that use wood or electricity as the evaporator fuel do see an increase in fossil emissions due to shipping inflows, as most of the emissions from producing maple syrup in these archetypes are either biogenic or electric. However, the greatest share of fossil emissions due to shipping inflows was from oil-fired cases due to increased fuel entering the operation. The greatest share of fossil emissions was 1.14% (M0 Oil).

In terms of syrup distribution, large-scale national retail scenarios can have significant fossil emissions. Since the burdens of distributing syrup for retail are a direct function of the amount of syrup being shipped, the impact of shipping falls within the range 0.0008-0.0015 kgCO_2e/gal-km, where packaging accounts for 7-13% of the weight. Retailing in bulk reduces the amount of material per gallon of syrup distributed, leading to lower emissions. The impact of producing the extra packaging (cardboard, plastic wrap, pallet bands) is also lower for majority bulk channels (0.02 vs. 0.08 kgCO_2e/gal). Emissions increase linearly with distance, so a national retail network has higher impact than a local one. Operations that emit fewer GHGs in the production process will have a larger portion of overall emissions from distribution than those who emit more in the production process. Similarly, those using an electric or wood-fired evaporator will have relatively higher fossil fuel emissions from distribution than those using fuel oil or other fossil fuels in their production process. In the worst case, (L1 with a 2,000 km average retail distance), distribution has the potential to be 27% of overall emissions and 33% of fossil emissions, giving it the potential to be a significant part of overall emissions per gallon.

Based on the results of our model, processing maple sap to syrup is the most energy and emissions intensive of the four production stages for almost all producers, regardless of size, except in the cases where vehicles dominate the collection stage and boiling reaches the limits of efficiency. As compared with the four production stages outlined in this paper, (sugarbush maintenance, sap collection, processing, and bottling) distribution has the potential to add significant emissions on a per gallon basis if the operation is already efficient, especially if the retail network is large and/or dominated by smaller retail containers. Shipping inflows are relatively small when compared to syrup distribution or compared to the four production stages listed above.

Guidance for Producers

The carbon footprinting analysis serves as an integration of LCA tools and engineering models to quantify the energy and emissions from the production of maple syrup. Producers can classify themselves within an archetype to see which technological decisions may benefit them most from an energy and emissions perspective. At all operational scales, producers should look to:

1. Decrease time spent boiling by concentration of sap (RO).
2. Increase heat transfer in their evaporator (use of preheaters, forced draft, etc.), especially for inefficient wood-fired evaporators.
3. Electrify as much of the operation as possible to reduce emissions by way of renewable electricity.
4. Introduce a vacuum tubing system to increase the amount of syrup produced relative to the energy and emissions inputs.

While processing and sap collection are responsible for the bulk of energy and emissions impacts, distribution should also be considered significant (>10% of processing emissions) if the retail network is large (>1000 km average) and/or the operation is already efficient (<10 kgCO_2e/gal).

Appendix A: Supporting Information

Data Collection

We engaged with the maple community via several mechanisms, including notices in the Maple Digest, email messages through state maple associations, and staffing a table in the trade show at the NAMSC annual meeting in Sturbridge, MA. In addition, the project PI has been an advisory member of the IMSI board of directors and has been active in their climate and environment committee for the past two years. The intent of this engagement was to recruit a cohort of producers across geography, size classes, and processing practices that we could interact with over the course of the project. The sap processing model described in this paper is a physics-based engineering model constructed primarily using basic thermodynamics and fluid mechanics, but also drawing from academic literature, conversations with university maple research personnel, maple extension publications, manufacturer data and conversations, and interactions with our producer cohort. We collected operational data from a diverse group of producers that we could use to inform the construction and parameterization of our sap processing model, as well as guiding the development of the archetypes that are central to our modeling effort. The data request that we used with producers is included in this SI. We have promised all the producers who share their data with us an annual report containing our analysis of their data from that year, including recommendations for GHG emissions reductions strategies.

The following five pages are a copy of the detailed annual data ask for the 2023 season:

Life cycle carbon footprint analysis and improvement strategies for US maple syrup production – data outline

This project is being conducted by researchers at the University of Michigan's Center for Sustainable Systems in the School for Environment and Sustainability, with the cooperation of the North American Maple Syrup Council. The research is funded through the USDA's ACER grant program. A significant part of the work depends on syrup producers sharing data on their production processes with the research team. This document outlines the data the research team is seeking.

We are looking for data on syrup production operations from the 2023 season through the 2025 season. The life cycle inventory data (detailed below) includes the land used to collect sap on and management activities on the land, the sap collection process, sap processing into syrup, and bottling/packaging. We're inventorying energy, process materials, building overhead, and non-durable equipment (with a lifetime of 10 years or less) used in sap processing and forestry operations, as well as collecting a description of capital equipment (buildings, vehicles, durable equipment) for each participating producer.

The first section below outlines the capital equipment inventory. Provide as much detail as possible, as this information is necessary to properly allocate the total energy and emissions to each process step and helps determine the process improvements that we'll be suggesting.

In the second section on total annual data, please record total annual data on maple sugaring operations (please do not include other farm or forest operations). **Please think of this second section as the minimum necessary data that we need to build a reasonably accurate model of your operations**.

In the third section on detailed data section please provide as much detailed data on your sugaring operations as you're able to. **Please think of this third section as the optional data section**. We understand that all producers and processors won't have the data recorded in the same level of detail as we're asking for in the detailed data section – often data will only be available in aggregate (for the whole sugar house, for example, but not for individual pieces of equipment). Please do fill out everything you're able to in the detailed data section, as any information helps us improve our modeling accuracy. When we collect data from you at the end of the season, we will also be asking you to rate the confidence you have in any estimates that you make (on a 5-point scale from not very confident to very confident).

Note that you'll need to pay attention to a few things right away in order to know where you're starting (electricity meters, vehicle odometers, tank fuel levels, etc.). Just like when you rent a car, it might be easiest to top off fuel tanks and start full, but it's okay to estimate if you're able to do it accurately.

If you have any questions about what we're looking for or want to talk through how to handle any unique details of your operations, please email the research team lead Geoff Lewis (glewis@umich.edu) any time.

We're looking forward to working with you and appreciate your interest, time, and effort!

Detailed annual data:

The land you collect sap on

a. How many separate land units (stands) do you collect sap on?
b. For each land unit
    i. Do you make syrup from this stand, do you hire a processor to boil and bottle it for you, or do you sell your sap to a processor?
    ii. Where is this stand located? (town, crossroads, …)
    iii. What is the area of this stand?
    iv. How many taps do you place in this stand?
    v. Is this stand managed solely for sap production?
        1. If no, what other products do you produce from this stand?
    vi. What forest management activities do you conduct on this stand?
        1. Thinning (removal of trees to promote maple release and growth)
        2. Brushing (removal of understory trees and shrubs, downed wood)
        3. Road construction/maintenance
        4. Lime or fertilizer application (in the past 10 years)
        5. Pest or disease management
    vii. What equipment do you use for the management activities selected above?
        1. Truck
        2. Tractor
        3. ATV
        4. snowmobile
        5. Chainsaw(s)
    viii. How much fuel did you use for these management activities?
        1. LPG
        2. Gasoline
        3. Diesel
        4. Chainsaw premix
        5. Electricity
            a. Grid
                i. Conventional
                ii. Renewable energy power purchase agreement
            b. Generator (type and amount of fuel)
            c. Renewable energy system

Sap Collection (for each stand listed above)

c. What kind of taps do you use?
    i. Brand/model/size
        1. Metal
        2. Plastic
d. How many taps are were replaced this year?
e. How many taps were added this year?
f. What method do you use to collect sap?
    i. Buckets
    ii. Sap Saks
        1. If yes, are these replaced every year?
    iii. Tubing

1. If yes,
    a. Estimate diameter, length, and material type (PE or PVC) installed
    b. Estimate length replaced this year, by type
    c. Estimate length added this year, by type
    d. Do you use a vacuum system or gravity?
        i. If vacuum,
            1. dates you started and stopped the pump <u>OR</u> total pump run time
            2. pump power rating
            3. electricity used and source
                a. grid, generator (gas, LPG)

g. Does your collection system use any of these to get sap to the sugar house?
    i. Pumps
    ii. Tractor
    iii. Truck
    iv. ATV
    v. How much electricity/fuel was used to operate these this year?

h. How much sap did you collect this year?

i. Please list the type and amount of the materials used in cleaning your sap collection equipment at the end of the season
    i. Water (amounts by source: well, municipal, RO wastewater)
        1. Hot
            a. Type and amount of fuel used to heat water
        2. Cold
    ii. Alcohol, others

Sap processing

j. Do you process only sap from your own stands, or do you process sap for others?
    i. If you process for others,
        1. distance sap is transported to your location from each producer
        2. transport mode (truck?)

k. How much sap did you process this year?

l. Are pumps used to move sap around and through your facility
    i. If yes, how much electricity was used for pumps this year <u>OR</u> total run time for each (& match run time with a pump in your capital equipment list)?

m. Do you use a reverse osmosis system?
    i. If yes, how much electricity was used for RO this year <u>OR</u> total run time?

n. For each evaporator in your processing facility
    i. Make and model
    ii. Size
    iii. Fuel type (wood, oil, pellets, LPG/propane, electricity)
    iv. Amount of fuel used in this evaporator this year
    v. Does this evaporator have a Steam-Away, or other efficiency-improving device?
        1. Describe this device (make & model)
    vi. Is the arch natural draft or fed with a blower?

vii. Type and amount of defoamer used this year

o. Do you process your syrup through a finisher?
   i. If yes, amount and type of fuel used this year.

p. What kind of filter system do you use for your syrup?
   i. Gravity cone
      1. How many filters (weight or number and size) did you use this year?
   ii. Press
      1. What size is your press?
      2. How much diatomaceous earth did you use this year?
      3. How many filters (weight or number and size) did you use this year?
   iii. Felt

q. How much syrup did you produce this year?

r. Estimate the amount (weight) of niter/sugar sand produced this year

s. Did you process any of your syrup further into maple cream, sugar, or hard candy?
   i. If yes, estimate the weight of each kind of maple product you produced beyond syrup this year.
   ii. Estimate the amount and type of electricity and fuels used for the additional process steps used for these products.

t. Please list the type and amount of the materials used in cleaning your sap processing equipment (RO, evaporator, finisher, pumps, tanks) at the end of the season
   i. Water (amounts by source: well, municipal, RO wastewater)
      1. Hot
         a. Type and amount of fuel used to heat water
      2. Cold
   ii. Alcohol, others

Bottling/packaging

a. Do you bottle and package only your own syrup?

b. Do you sell finished syrup to a bottler/packager?

c. Do you buy finished syrup from producers to bottle/package?

d. If you bottle/package syrup
   i. Amount of syrup bottled/packaged
   ii. Type and amount of fuel used by bottling machinery
      1. Electricity
      2. Natural gas
      3. Other

e. Please list number, size, material, weight, and source of bottles used this year

	Number	Size	Material	source
example	*10,000*	*1-qt*	*HDPE*	*Sugarhill*

f. Do you retail all or part of your production from your processing facility or at a farmer's market?
    i. If yes, what amount or fraction of your production do you retail?
g. Do you ship all or part of your production for retail elsewhere?
    i. If yes, what amount of your production did you ship this year?
    ii. Transportation mode, distance, and fuel used in shipping to each distributor/retailer
        1. Car/pickup truck
        2. Heavy-duty truck
        3. Other (identify)

Sugarbush Maintenance and Management

Sugarbush maintenance and management involves activities that are performed in the offseason, i.e., brush thinning, wood cutting, fertilizing (albeit rare in the current industry), etc. For producers who use wood, we assume that all wood is gathered on site using a combination of a chainsaw, a tractor, and a wood splitter.[59] All producers, regardless of whether they use wood as an evaporator fuel, are assumed to use a chainsaw. However, those that do not use wood are assumed to use the chainsaw proportionally less over the course of the season, resulting in less fuel use. Referencing the Stihl catalog, a small, medium, and large chainsaw (4.75 hp, 6 hp, 7.5 hp) were assigned to each archetype scale as well as the number of saws used.[60,61] For small and medium sized producers, we assume that two saws would be operated alternately, with more use in the medium sized operation. For large producers, we assume three saws as we expect multiple people would be working at any given time in a larger operation.

Table S2: Equipment inventory for sugarbush maintenance and management used to construct the LCA model.

Equipment	Size (single unit)	Weight (kg/unit)	Units	Design Life	Notes & Assumptions
Chainsaw	Small (4.75 hp)	5.35	kg	10 yr.[62]	Material: Stainless Steel, Proxy: STIHL Chainsaws[61] averaged catalogue to find weight and hp for each size category Blade weight was calculated from separate source[63]
Chainsaw	Medium (6 hp)	6.28	kg	10 yr.	Material: Stainless Steel, Proxy: STIHL Chainsaws[61] averaged catalogue to find weight and hp for each size category Blade weight was calculated from separate source[63]
Chainsaw	Large (7.5 hp)	8.75	kg	10 yr.	Material: Stainless Steel, Proxy: STIHL Chainsaws[61] averaged catalogue to find weight and hp for each size category Blade weight was calculated from separate source[63]
Brush Mower	Small (4')	210.45	kg	15 yr.	Material: Stainless Steel, Proxy: CountyLine 4 Ft. Round Back Rotary Cutter,[64] Design Life assumed to be twice as long as landscaping equipment[65,66]
Brush Mower	Medium (5')	240.91	kg	15 yr.	Proxy: CountyLine 5 Ft. Round Back Rotary Cutter[67]
Brush Mower	Large (6')	283.18	kg	15 yr.	Proxy: CountyLine 5 Ft. Round Back Rotary Cutter[68]
Snowblower	Small (54")	288.64	kg	20 yr.	Material: Stainless Steel, Proxy: Erskine 3 Point PTO Model 520RM[69]
Snowblower	Medium (60")	300.00	kg	20 yr.	Proxy: Erskine 3 Point PTO Model 620RM[70]
Snowblower	Large (72")	340.91	kg	20 yr.	Proxy: Erskine 3 Point PTO Model 725RM[71]
Tractor	45 hp[72–75]	1,818.18	kg	10,000 hr.[76]	Energy/Emissions scaled by weight compared to ICEV (~1,346 kg) Weight was a benchmark average for tractor data from producers
Wood Splitter	20 Ton Force	181.82	kg	20 yr.	Material: Stainless Steel Proxy: Wallenstein WX520 Horizontal Log Splitter[59]

In terms of fuel, we estimate of ratio of 1:1 gallons of chainsaw bar oil to gallons of premix was used throughout the season.[61,77] For a wood splitter, we assume a 20-ton force wood splitter working at a high enough speed to process the amount of wood needed in the largest wood consumption case (M0). Fuel use by the wood splitter was calculated by estimating the cutting capacity of a 20-ton wood splitter at 1 cord/hour,[78,79] with a brake specific fuel consumption of 250 g/kWh for gasoline.[80] For equipment that uses standard gasoline or diesel, brake specific fuel consumption (BSFC) was used to account for motor efficiency losses; diesel was calculated using a BSFC rate of 200 g/kWh and gasoline 250 g/kWh.[80] The average density of the fuel was then used to compute the consumption rate in gal/hp-hr.[81] For the wood splitter, a horsepower rating of 6.5 hp was used for the 20-ton force case.[59] Combustion emissions from chainsaw and wood splitter use were approximated based on the fuel consumption and not engine condition or age. Snow blowers and brush mowers were also included in maintenance activities and were modeled as power take-off (PTO) equipment.[64,67–71] The fuel emissions for these pieces of equipment were included in the fuel used by the tractor, and factored into the 75% full rated power time of use in the fuel consumption equation outlined by Grisso 2020.[82,83] The horsepower of a tractor used in sugaring was estimated to be around 45 hp (42 hp PTO rated power) based on producer data.[72–75] Tractor use was estimated based on use hauling wood, using PTO equipment and, loading/unloading other equipment in the absence of a forklift.[84] It was assumed that 20 trips of a half mile (round trip) per 1,000 taps would be made for those using wood as an evaporator fuel versus 5 trips for non-wood fired operations.[84] Tractor hours for these trips were calculated using the total mileage and an average speed of 4.5 mph. It was assumed that the use of PTO equipment with the tractor would scale with operation size, as their use is dependent on land area. Small operations were assumed to use PTO equipment for a total of 30 hours (15 hrs. plowing, 10 hr. mowing, and 5 hrs. unloading), medium sized operations ran PTO for 70 hrs. (30 hrs. plowing, 20 hrs. mowing, and 20 hrs. unloading), and large operations ran PTO for 100 hrs. (40 hrs. plowing, 30 hrs. mowing, and 30 hrs. unloading). Design lives were assumed based on averages for heavy machinery but can vary widely based on maintenance. We assume that equipment expected to be used more often had a slightly shorter design life (10 years) and equipment used seasonally was expected to remain usable for longer (20 years). For tractors, the design life was assumed to be 10,000 hours with proper maintenance.

Table S3: Archetype inventory for sugarbush maintenance and management for small producers. The information in this table was fed through the LCA model to generate results on emissions and energy for this process stage.

ID		S0 wood	S0 oil	S1 wood	S1 oil	S2 wood	S2 oil	S3 wood	S3 oil	S4 wood	S4 oil	S5 wood	S5 oil
Capital Equipment	Chainsaw (#, hp)	(2,4.75)	(2,4.75)	(2,4.75)	(2,4.75)	(2,4.75)	(2,4.75)	(2,4.75)	(2,4.75)	(2,4.75)	(2,4.75)	(2,4.75)	(2,4.75)
	Premix	1	0.5	1	0.5	1	0.5	1	0.5	1	0.5	1	0.5
	Bar Oil	1	0.5	1	0.5	1	0.5	1	0.5	1	0.5	1	0.5
	Brushmower (PTO)	Small (4')	Small (4')	Small (4')	Small (4')	Small (4')	Small (4')	Small (4')	Small (4')	Small (4')	Small (4')	Small (4')	Small (4')
	Snowblower (PTO)	Small (54")	Small (54")	Small (54")	Small (54")	Small (54")	Small (54")	Small (54")	Small (54")	Small (54")	Small (54")	Small (54")	Small (54")
	Tractor Hrs.	31.17	30.29	31.17	30.29	31.17	30.29	31.17	30.29	31.17	30.29	31.17	30.29
	Tractor Fuel (gal diesel)	67.10	65.21	67.10	65.21	67.10	65.21	67.10	65.21	67.10	65.21	67.10	65.21

	Wood Splitter (W.S.)	20 Ton Force	0	20 Ton Force	0	20 Ton Force	0	20 Ton Force	0	20 Ton Force	0	20 Ton Force	0
	W.S. Fuel (gal gasoline)	1.80	0.00	1.80	0.00	1.80	0.00	3.93	0.00	0.78	0.00	0.68	0.00
Agricultural Inputs	Fertilizer	0	0	0	0	0	0	0	0	0	0	0	0
	Lime	0	0	0	0	0	0	0	0	0	0	0	0

Table S4: Archetype inventory for sugarbush maintenance and management for medium and large producers. The information in this table was fed through the LCA model to generate results on emissions and energy for this process stage.

ID		**M0 Wood**	**M0 Oil**	**M1 Wood**	**M1 Oil**	**M2 Wood**	**M2 Oil**	**M3 Wood**	**M3 Oil**	**M4 Electric**	**L0 Oil**	**L1 Electric**
Capital Equipment	Chainsaw (#, hp)	(2, 6)	(2, 6)	(2, 6)	(2, 6)	(2, 6)	(2, 6)	(2, 6)	(2, 6)	(2, 6)	(3,7.5)	(3, 7.5)
	Premix	4	2	4	2	4	2	4	2	2	8	8
	Bar Oil	4	2	4	2	4	2	4	2	2	8	8
	Brushmower (PTO)	Medium (5')	Medium (5')	Medium (5')	Medium (5')	Medium (5')	Medium (5')	Medium (5')	Medium (5')	Medium (5')	Large (6')	Large (6')
	Snowblower (PTO)	Medium (60")	Medium (60")	Medium (60")	Medium (60")	Medium (60")	Medium (60")	Medium (60")	Medium (60")	Medium (60")	Large (72")	Large (72")
	Tractor Hrs.	81.20	72.80	81.20	72.80	81.20	72.80	81.20	72.80	72.80	108.13	108.13
	Tractor Fuel (gal diesel)	174.78	156.70	174.78	156.70	174.78	156.70	174.78	156.70	156.70	232.76	232.76
	Wood Splitter (W.S.)	20 Ton Force	0	20 Ton Force	0	20 Ton Force	0	20 Ton Force	0	0	0	0
	W.S. Fuel (gal Gasoline)	17.14	0.00	2.01	0.00	4.41	0.00	3.83	0.00	0.00	0.00	0.00
Agricultural Inputs	Fertilizer	0	0	0	0	0	0	0	0	0	0	0
	Lime	0	0	0	0	0	0	0	0	0	0	0

Sap Collection

Vehicles used in sap collection vary depending on the operation size, land area, distance to the sugarhouse, and the terrain of the sugarbush. For the purposes of creating a generic archetype with the most used equipment, a pickup truck and a UTV were selected as the primary methods of transportation in and around the sugarbush for collecting/hauling sap, checking lines, and tapping trees. It was assumed that a pickup truck with an attached trailer would be used for hauling sap at all scales, however, for the largest operations, vehicles larger than a pickup truck may be used.[84] A UTV was modeled as the primary vehicle for moving around the sugarbush, as a snowmobile and an ATV have similar fuel consumption characteristics and weights.[38,39] While the distances traveled vary based on sugar house position and total size of the sugarbush among operations with identical equipment, we made assumptions about distances traveled based upon trends corresponding to producer behavior at different production scales, producer data, and expert consultation.[46,76,84] It was assumed that without a tubing system, collection would be done primarily via vehicle (split between the two types listed in Tables S4 and S5). As production scale increases, so does the acreage of the sugarbush, increasing all sugarbush-related activities involving a UTV. Vehicle use for each archetype size was calculated using a combination of producer data for the 2023 season and the expert consultation of Adam Wild of the Cornell University Uihlein Maple Research Forest. It was assumed that a UTV would be used for tubing system maintenance, pump checking, tapping/untapping trees, as well as checking buckets.[84] It was assumed that with a tubing system in place, this would amount to around 55 three-quarter mile trips per 1,000 taps per year, while those on buckets (S0 archetypes) would make 30 such trips over the course of the year. The average fuel economy of a UTV was estimated at 10 mpg when factoring in idling (normally 20 mpg).[85] For sap hauling, it was assumed around 75-80% of all producers would use vehicles to haul sap in some capacity, with the total distance traveled being related to the acreage of the operation, and the number of boils.[84] An average of 1.5 round trips per boil were assumed, with small producers having a 5 mile round trip, medium having a 10 mile round trip, and large having a 15 mile round trip.[84] It was assumed that sap hauling for buckets would result in two times the distance as compared to those with a tubing system.[84] Hauling sap on a trailer has an effect on the fuel economy of the pickup, so a fuel economy adjustment was placed on the mileage traveled for hauling sap. The fuel reduction value (FRV) for a pickup that weighs 4,491 lbs and has a fuel economy of 14.7 mpg (as specified by the 2011 simulation year in GREET) was calculated using the methods of Kim and Wallington (2013), without the adjustment for mechanical efficiency specific to the vehicle type.[86] The average fuel-mass coefficient for vehicles ~2,000 kg presented in the paper was 0.38. The FVR was then applied to the average weight (half a trip full GWVR weight and half a trip empty weight) of the sap hauling trailer (using a proxy of a 550-gal trailer for small producers and 1,600-gal trailer for medium and large producers).[87,88] This value was then added to the fuel consumption of the pickup to get total fuel consumption per mile and inverted to get the average adjusted fuel economy for the sap hauling trip. The embodied emissions and energy of production for the trailer were excluded from the modeling efforts. Other pickup truck usage from miscellaneous travel could include purchasing supplies, bringing equipment in for servicing, and hauling fuels like gasoline or diesel for pumps and other vehicles.[84] These miscellaneous activities can varied widely, and among producer data they tended to increase in producer size; small producers ranged from 56-1,243 mi, medium ranged from 60-4,200 mi, and large ranged from 1,820-11,000 mi; however, some of these trips included travel to conferences and long distance small-scale retail, which are not included in the vehicle use for sap collection. Small operations were assumed to have 300 mi. of travel, medium operations were assumed to have 600 mi. and large were assumed to have 1,200 mi.

Table S5: Equipment inventory for sap collection used to construct the LCA model.

Equipment	Size (single unit)	Weight (kg/unit)	Units	Design Life	Notes & Assumptions
Pickup Truck	Standard (GREET)		kg	180,000 mi	Average Fleet Age (12 yrs.—GREET Simulation: 2011) Note: GREET has a 5-year modeling lag for cars (2006)

UTV	Standard (See notes)	545.45	kg	10,000 mi[89]	Energy/Emissions scaled by weight compared to ICEV (~1346 kg) Proxy: Polaris Ranger SP 570[90]
Buckets[91]	1 gallon	0.693	kg	50 yr.	Material: Stainless Steel
Polycarbonate Taps[92]	5/16"[53]	0.007	kg	1 yr.	Material: Polycarbonate
Polycarbonate Fittings & End hooks[93]	5/16"	0.0318	kg	3 yr.	Material: Polycarbonate Average weight of plastic T's and connectors, adjusted for polycarbonate density
Aluminum Taps[94]	5/16"	0.0076	kg	10 yr.	Material: Aluminum Assumed replacement same as tubing saddles based on seasonal wear Estimate for product weight is the listed weight is for the 6-pack
Tubing Saddles (Clamps)[95]	2"	0.091	kg	10 yr.	Material: Stainless Steel
5/16" Drop Line[96]	5/16" diameter	0.014	kg/foot	3 yr.[46]	Material: LDPE
5/16" Lateral[96]	5/16" diameter	0.014	kg/foot	10 yr.[46]	Material: LDPE
3/4" Mainline[97]	3/4" diameter	0.036	kg/foot	25 yr.[46]	Material: HDPE
1" Mainline[98]	1" diameter	0.064	kg/foot	25 yr.	Material: HDPE
1-1/4" Mainline[99]	1-1/4" diameter	0.082	kg/foot	25 yr.	Material: HDPE
1-1/2" Mainline[100]	1-1/2" diameter	0.091	kg/foot	25 yr.	Material: HDPE
2" Mainline[101]	2" diameter	0.182	kg/foot	25 yr.	Material: HDPE
Support Wire[102]	12.5 gauge	0.011		10 yr.	Material: Stainless Steel
0.9 hp Vacuum Pumps[49,103]	0.9 hp	19.25	kg	15 yr.	Proxy Becker Pumps (Industry Data) Took linear fit of weight, energy, and emissions for Becker Maple Series pumps
3.5 hp Vacuum Pumps[49,103]	3.5 hp	74.87	kg	15 yr.	Proxy Becker Pumps (Industry Data) Took linear fit of weight, energy, and emissions for Becker Maple Series pumps
15 hp Vacuum Pumps[49,103]	15 hp	320.85	kg	15 yr.	Proxy Becker Pumps (Industry Data) Took linear fit of weight, energy, and emissions for Becker Maple Series pumps
0.75 hp Process Water Pump[104]	0.75 hp	2.93	kg	15 yr.	Material: Cast Iron Proxy HYPRO pump Took linear fit of weight, energy, and emissions for suite of process pumps
2 hp Process Water Pump[104]	2 hp	7.82	kg	15 yr.	Material: Cast Iron Proxy HYPRO pump Took linear fit of weight, energy, and emissions for suite of process pumps
Stainless Steel Storage Tank[105,106]	y gal	$1.589\ y^{0.6383}$	kg	50 yr.	Assuming vertical tank
HDPE Storage Tank	y gal	$1.195\ y^{0.6603}$	kg	50 yr.	Assuming vertical tank Assuming 0.5-inch thickness[107,108]
Hydrogen Peroxide[41]	1 gal	4.64	kg/gal	1 yr.	50% dilution
Chlorine Bleach[41]	1 gal	3.92	kg/gal	1 yr.	35% dilution
Horizontal 1x0.5 hp Releaser[109]	18" x 48"	68.18	kg	15 yr.	Material: Stainless Steel

Horizontal 2x2 hp Releaser	18" x 48"	109.09	kg	15 yr.	Material: Stainless Steel
Horizontal 4x2 hp Releaser	18" x 60"	195.45	kg	15 yr.	Material: Stainless Steel

The scenario inventory values for the tubing system in Table S5 were calculated based on the tubing and vacuum model outlined in Checkoway 2024b (Appendix C),[50] assuming 100 tappable trees per acre, 1.0 cubic feet per minute (CFM) of air leakage per 100 taps, 3 ft. of drop line per tap, 6 taps per lateral, a 2-grade slope, 100 ft. of space between mainlines, and a starting length of 50 ft. of mainline from the collection point to the first mainline. The system was set up to allow for 25” Hg vacuum, meaning the factor of safety nominal size change was not used, as the system would have to be in near optimal conditions to hold this level of vacuum. The results generated represent the average tubing diameter needed across the tubing system, even though it is likely that varying lengths of multiple diameters may be necessary depending on the physical conditions of the land. It was assumed that there were ~1.5 fittings per lateral (each tap has a tee, 1 straight connector per 10 taps, big tee per lateral)[55] with an average replacement time of 3 years. Tubing saddles (clamps) were assumed to be single size for all main line diameters and are used to help hold the tension wire in place.[95] We assume that there was a saddle for every three feet of mainline and an extra saddle for every lateral line.[110] Buckets were assumed to be one gallon each with a design life of 50 years, and corresponding taps were assumed to be aluminum with a design life of 10 years. The long design life of buckets was based on producer data, where some having buckets over 100 years old. 12.5-gauge stainless steel support wire was assumed to run the length of the main line, and 3’ of run was accounted to secure it to a tree every 9’ of mainline as well as a 2” wire tie spaced every foot of line.[110]

Vacuum pumps were sized to have a single vacuum pump with the necessary power to maintain vacuum in the tubing system (if they maintain a removal rate of air higher than the total leakage rate). Vacuum tubing system calculations are outlined in Checkoway 2024b (Appendix C).[50] Vacuum pump horsepower served as the anchor for these calculations and were based on the ratings in the Becker Pump catalog with respect to the number of taps served.[49] We assume that a vacuum pump runs constantly for the duration of the season, and this period defined its annual electricity use. We define the season according to the 10 year average season length (2013-2022) from the USDA NASS statistics, which totaled 32.93 days (or 790.32 hours).[111] The horsepower-hours (hp-hr) were then converted to kWh to obtain electrical energy over the course of the season, assuming a 75% motor efficiency and a 90% pump efficiency (for a total efficiency of 67.5%).[112,113] Producers may use variable frequency drive (VFD) on their vacuum pumps to increase efficiency, however, for a conservative estimate it was assumed that a VFD system was not used. Weight, energy, and emissions from producing the pump were based on a linear fit of Becker’s maple series pumps; production energy is 1449x, production emissions are 80.47x, and weight (kg) is 21.39x, where x is the horsepower of a standard vacuum pump.[103] A releaser is also needed, with its own energy consumption based on the total amount of sap being moved from the manifold and the process flow rate.[114] The size of the releaser was based on the CDL catalog and the number of taps each unit could serve.[109] The flow rate of the pumps were based on the flow rates of the HYPRO process pumps of the same horsepower at 100 PSI (324 GPH for the 0.5 hp and 1,014 GPH for the 2 hp pumps).[104] The same efficiency was used for releaser pump energy consumption as for vacuum pump energy.

Process pumps were assumed to be used to transport sap from a collection location to the sugar house to be boiled. Process pumps were sized with respect to the releaser that *would* be necessary if the tubing collection system had a vacuum pump (using the same flow rates as the releaser to move an equivalent amount of sap).[104] All archetypes were assumed to use process pumps to transfer sap, with small using a single 0.5 hp, medium using two 2 hp, and large using four 2 hp pumps. The brake specific fuel consumption for gasoline was used to calculate fuel consumption per hp-hr.[80] The production of process pumps was also approximated by a linear fit of HYPRO model pumps at different horsepower (production energy is 124.96x, production emissions are 3.37x and pump weight (kg) is 3.91x, where x is horsepower).[104]

Storage tanks were assumed to be slightly oversized with respect to the amount of sap collected over the course of the season based on variation in each year's sap run.[105] Based on conversations with producers, many buy the largest single collection vessels they can in order to hold large volumes of sap for short periods of time before either boiling or storing it.[106] Therefore, the total sap held for a boil was rounded to the nearest hundred, up to 2,500 gallons. If the total sap held per boil on average was larger than 2,500 gallons, the total sap was divided by 2,500 and rounded to determine the total number of tanks (a conservative estimate). This total was doubled to account for an equal number of HDPE tanks of the same size used for hauling sap to the sugarhouse. The weights of tanks were calculated on a power fit with stainless tanks being $3.4958y^{0.6383}$, with y being gallons of capacity. HDPE tank weights were calculated using the dimensions of the stainless tanks, an assumed wall thickness of 0.5 inches, and the ratio of material densities of HDPE and stainless steel. The HDPE tanks had a power fit of $2.6288y^{0.6603}$.

Chlorine bleach and hydrogen peroxide were chosen as disinfectants for the tubing system and buckets. Bleach was primarily used for bucket disinfection, with 1 part chlorine bleach to 20 parts water.[115] We assume that each bucket would require ¼ of its one-gallon capacity for a full wash at the end of the season. Hydrogen peroxide was chosen as the disinfectant for tubing systems, with 18 oz. cleaning 65 taps worth of tubing. [115]

Table S6: Archetype inventory for small, medium, and large producers of all fuel types. The information in this table is fed through the LCA model to generate emissions and energy intensity.

ID		S0 wood	S0 oil	S1 wood	S1 oil	S2 wood	S2 oil	S3 wood	S3 oil	S4 wood	S4 oil	S5 wood	S5 oil	M0 Wood	M0 Oil	M1 Wood	M1 Oil	M2 Wood	M2 Oil	M3 Wood	M3 Oil	M4 Electric	L0 Oil	L1 Electric
Personal Vehicles	Pickup Truck (mileage)	600	600	600	600	450	450	450	450	450	450	450	450	975	975	975	975	975	975	975	975	975	1875	1875
Farming Vehicles	UTV Mileage	11.9	11.9	11.9	11.9	21.8	21.8	21.8	21.8	21.8	21.8	21.8	21.8	207.9	207.9	207.9	207.9	207.9	207.9	207.9	207.9	207.9	603.9	603.9
	UTV Fuel[85]	1.19	1.19	1.19	1.19	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79	20.79	60.39	60.39
Direct Collection Equipment	Taps (S0 alum. rest polycarb.)	528	528	528	528	528	528	528	528	528	528	528	528	5040	5040	5040	5040	5040	5040	5040	5040	5040	14640	14640
	Polycarbonate Fittings and End hooks	0	0	0	0	792	792	792	792	792	792	792	792	7560	7560	7560	7560	7560	7560	7560	7560	7560	21960	21960
	Tubing Saddles	0	0	0	0	934	934	934	934	934	934	934	934	9390	9390	9390	9390	9390	9390	9390	9390	9390	27510	27510
	Buckets	528	528	528	528	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5/16" Drop Line (ft)	0	0	0	0	1584	1584	1584	1584	1584	1584	1584	1584	15120	15120	15120	15120	15120	15120	15120	15120	15120	43920	43920
	5/16" Laterals (ft)	0	0	0	0	9856	9856	9856	9856	9856	9856	9856	9856	95760	95760	95760	95760	95760	95760	95760	95760	95760	283040	283040
	Main Line Size #1 (diam [in], length [ft])	0	0	0	0	(3/4", 2,537)	(3/4", 2,537)	(3/4", 2,537)	(3/4", 2,537)	(3/4", 2,537)	(3/4", 2,537)	(3/4", 2,537)	(3/4", 2,537)	(1", 25,649)	(1", 25,649)	(1", 25,649)	(1", 25,649)	(1", 25,649)	(1", 25,649)	(1", 25,649)	(1", 25,649)	(1", 25,649)	(1-1/2", 31,214)	(1-1/2", 31,214)
	Main Line Size #2 (diam [in], length [ft])	0	0	0	0	(1",0)	(1",0)	(1",0)	(1",0)	(1",0)	(1",0)	(1",0)	(1",0)	(1-1/4", 0)	(1-1/4", 0)	(1-1/4", 0)	(1-1/4", 0)	(1-1/4", 0)	(1-1/4", 0)	(1-1/4", 0)	(1-1/4", 0)	(1-1/4", 0)	(2", 43,995)	(2", 43,995)
	12.5-Ga. Wire Support (ft)	0	0	0	0	3805	3805	3805	3805	3805	3805	3805	3805	38473	38473	38473	38473	38473	38473	38473	38473	38473	112813	112813
Pumps	Vacuum Pump (hp)	0	0	0	0	0	0	0.9	0.9	0.9	0.9	0.9	0.9	0	0	0	0	3.5	3.5	3.5	3.5	3.5	15	15
	Vacuum Pump Fuel (kWh)	0	0	0	0	0	0	786	786	786	786	786	786	0	0	0	0	3056	3056	3056	3056	3056	13096	13096
	Process Pump (# x hp)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	2x2	2x2	2 x 2	2x2	2 x 2	2x2	2 x 2	2x2	2x2	4x2	4x2

	Process Pump Fuel (gal diesel)	0.43	0.43	0.43	0.43	0.43	0.43	0.94	0.94	0.94	0.94	0.94	0.94	10.49	10.49	10.49	10.49	22.95	22.95	22.95	22.95	22.95	133.33	133.33
Storage	Storage Tank Capacity (gal)	300	300	300	300	300	300	500	500	500	500	500	500	1700	1700	1700	1700	2500	2500	2500	2500	2500	2500	2500
	# Tanks	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	4	4	4	4	4	8	8
Disinfect Agents	Hydrogen Peroxide (gal)[115]	0.00	0.00	0.00	0.00	1.142	1.142	1.142	1.142	1.142	1.142	1.142	1.142	10.904	10.904	10.904	10.904	10.904	10.904	10.904	10.904	10.904	31.673	31.673
	Chlorine Bleach (gal)[115]	6.29	6.29	6.29	6.29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Releasers	Horizontal Releaser Model	0	0	0	0	0	0	18"x 48" 0.5 hp	18"x 48" 0.5 hp	18"x 48" 0.5 hp	18"x 48" 0.5 hp	18"x 48" 0.5 hp	18"x 48" 0.5 hp	0	0	0	0	18"x48" (2x2hp)	18"x48" (2x2hp)	18"x48" (2x2hp)	18"x48" (2x2hp)	18"x48" (2x2hp)	18"x60" (4x2hp)	18"x60" (4x2hp)
	Releaser Fuel (kWh)[116]	0.00	0.00	0.00	0.00	0.00	0.00	15.76	15.76	15.76	15.76	15.76	15.76	0.00	0.00	0.00	0.00	384.55	384.55	384.55	384.55	384.55	2234.06	2234.06

Processing

Evaporators were sized to handle the amount of sap boiled throughout the season (Table S7). The amount of sap collected was calculated based on the number of taps, a conservative estimate of eight gallons of sap per tap (baseline gravity collection),[35,54,55,117,118] an average tree internal pressure of 25 PSI,[53] and the vacuum held by the tubing system (which we modeled at 25" Hg). Detailed calculations of sap yield with vacuum are presented in Checkoway 2024b (Appendix C).[50] The volume of sap was divided into runs, where the number of boiling runs was assumed to vary with producer size, with smaller producers needing to boil slightly less frequently (20 runs), medium sized (25 runs), and large producers (30 runs).[46] The size of an evaporator was assumed to stay consistent across each producer size class, meaning it would be unlikely for a producer to size down an evaporator even as their operation becomes more efficient. Using the UNH Extension guide for evaporation rates for different sizes of evaporator, the hours a run would take were calculated based on the input °Bx.[119] The smallest evaporator that would produce a reasonable boiling time (<18.5 hours) was selected for that size class. This estimate was evaluated by an industry expert for the most probable evaporator size at a specific number of taps (Table S6).[46]

Table S7: Example sap boiling run scenario for different input Brix at 14,640 taps with 12.5" hg vacuum, 5'x14' evaporator, and 30 runs

Input °Bx	gals sap per gal syrup	gal sap boiled per hr.	gal sap per run	hrs. per run	gal syrup per hr.	gal syrup processed per season	Total Time Saved (hrs.)
2.00	44.24	230.00	6185.42	26.89	5.20	4194.46	0.00
4.00	21.95	230.00	2996.58	13.03	10.73	4194.46	415.94
8.00	10.80	230.00	1401.88	6.10	22.94	4194.46	623.94
12.00	7.09	230.00	870.88	3.79	36.93	4194.46	693.20
16.00	5.23	230.00	605.10	2.63	53.14	4194.46	727.87
20.00	4.12	230.00	445.88	1.94	72.12	4194.46	748.64
24.00	3.38	230.00	339.74	1.48	94.65	4194.46	762.48
67.00	1.00	230.00	0.00	0.00	--	--	806.80

We used the CDL Master-E as the electric evaporator, and manufacturer specifications were used to determine the process rate rather than size (as they do not boil at atmospheric pressure).[120] The Master-E is currently only manufactured in a 54 sq. ft. surface area model, so there was no variation in the electric evaporator modeled for medium versus large producers (scenarios M4 and L1). In order to produce the same syrup product in the electric evaporator as the other archetypes, it has to be brought up to the boiling point to undergo a Maillard reaction after it is drawn off.[121,122] It was assumed an electric steam kettle would be used to bring the total volume of 67 °Bx syrup to temperature at a heat transfer efficiency of 75%, and the total energy needed in specific heat consumption was converted to kWh.[123] The calculations in Checkoway 2024a (Appendix B) were used to estimate the amount of fuel needed for boiling in each of the scenarios.[56] For the wood-fired archetypes, a 50/50 average emissions and split energy for softwood and hardwood was used in calculations. For simplicity, a blower was not factored in for the oil-fired evaporator due to its small relative impact; the energy consumption from a ½ hp blower running for the total length of all boils (as calculated by the methods of table S6) at 65% efficiency ranged from 0.06% (M1) to 0.81% (S5) of the total energy from boiling alone over the course of the year for the oil-fired scenarios.

Using the same method as above, we sized reverse osmosis (RO) equipment based on the number of gallons of sap boiled per hour.[124] In an ideal process, the flow rates of the RO and the evaporator would be the same, with the sap coming out of the RO at the same rate as it would be boiled on the pan, without intermediate storage.[125] The models of RO were selected based on their flow rates assuming this ideal process condition (Econox models from H_2O Innovation were selected as proxies for these calculations). To reduce RO cost, the smallest viable configuration of RO housing and number of membranes (posts) was selected for each producer size. Each RO was then assumed to run at full power at their respective maximum process rates. The number of hours the RO was running was estimated by using gallons per hour and the total number of gallons of sap processed throughout the year. Additionally, it was assumed a washing cycle equal to the number of hours run per season would be run with just the ratio of power of the feed pump to the total horsepower of all the pumps in the unit. Using manufacturer specifications for volts/amps, the number of kWh was calculated for a season. In the case of the electric evaporator (M4 and L1), the optimal working conditions of the arch require 30 °Bx input.[120] We assume that the Econox 2000 models that achieve 15 °Bx could take two passes of sap to double the concentration from 15 to 30 °Bx. The total electricity was then calculated as the amount of electricity needed to run all the season's sap through a single time, and then the smaller volume of now concentrated sap. The volume of concentrated sap would be less than that of the initial 2 °Bx that passed through the machine the first time. This new volume was calculated by the ratio of input °Bx to output °Bx (giving you the remaining percentage of liquid per gallon processed). This total was multiplied by the total number of gallons collected over the course of the year to determine the total volume of the second pass of sap through the RO. Using this volume and the process rate, the total number of kWh were calculated.

Table S8: Equipment inventory for the processing stage used to build the LCA model.

Equipment	Size (single unit)	Weight (kg/unit)	Units	Design Life	Notes & Assumptions
2' x 6' Wood-Fired Arch[126]	2' x 6'	897.00	kg	50 yr.	0.5-gal refractory cement, 70 fire bricks, 24 sq ft ceramic wool[127] Arch Material: Stainless Steel
4' x 12' Wood-Fired Arch	4' x 12'	2187.00	kg	50 yr.	2.5-gal refractory cement, 235 fire bricks, 96 sq ft ceramic wool Arch Material: Stainless Steel
2' x 6' Oil-Fired Arch	2' x 6'	580.00	kg	50 yr.	24 sq ft ceramic wool Arch Material: Stainless Steel
4' x 12' Oil-Fired Arch	4' x 12'	1225.00	kg	50 yr.	96 sq ft ceramic wool Arch Material: Stainless Steel
5' x 14' Oil-Fired Arch	5' x 14'	1686.00	kg	50 yr.	140 sq ft ceramic wool Arch Material: Stainless Steel

Master-E Electric Evaporator[120,128]	54 sq ft	3233.00	kg	50 yr.	112 sq ft ceramic wool Arch Material: Stainless Steel
Ceramic Insulation[37,129]	1 sq ft	0.038	kg/cuft	10 yr.	1-inch-thick sheet
Fire Brick[43]	1 brick	2750	kg/m^3	50 yr.	Calcium-Aluminum-Cement Castable (refractory brick)
Refractory Cement[43]	1 gal	2380	kg/m^3	50 yr.	Calcium-Aluminum-Cement Castable (conventional)
Econox 600 RO[124,130]	1 post / 550 gph	268.18	kg	15 yr.	Material: Stainless Steel
Econox 1200 RO	2 post / 950 gph	336.36	kg	15 yr.	Material: Stainless Steel
Econox 2000 RO	4 post / 1600 gph	459.09	kg	15 yr.	Material: Stainless Steel
Econox 2000 RO	6 post / 2000 gph	568.18	kg	15 yr.	Material: Stainless Steel
Small Filter Press[131–134]	7" Plate	36.36	kg	15 yr.	Assumed: 70%-30% Aluminum/SS
Medium Filter Press	10" Plate	56.82	kg	15 yr.	Assumed: 70%-30% Aluminum/SS
Large Filter Press	20" Plate	136.36	kg	15 yr.	Assumed: 70%-30% Aluminum/SS
Filter Paper[135]	1 sq ft	0.014	kg/sq ft.	1 yr.	Approximated Polyester
Gravity Filter Tank[136]	5 gal	11.85	kg	20 yr.	Material: Stainless Steel Amount of material calculated based on dimensions of tank and assumed thickness of 0.12 inch
Filter Cone[137]	8 quarts	0.15	kg	10 yr.	Approximated Polyester
Filter Cone Rack[138]	8 quarts	0.43	kg	20 yr.	Fry Oil Stainless Steel Rack
Diatomaceous Earth[37]	1 gal	1.89	kg/gal	1 yr.	Proxy: Sand
Pan Cleaner[37,139]	1 gal	7.12	kg/gal	1 yr.	Phosphoric Acid
Defoamer Non-organic[37]	1 gal	3.94	kg/gal	1 yr.	Propylene Glycol
Citric Acid[45]	1 gal	6.28	kg/gal	1 yr.	Weight Based on Material Density
Glycol[37]	1 gal	3.94	kg/gal	1 yr.	Propylene Glycol
RO Soap[37]	1 gal	8.06	kg/gal	1 yr.	Sodium Hydroxide

Gravity filtering utilizes a filter tank, filter cone, and a rack to support the cone as syrup is poured through it. Filter cones can be reused multiple times over the course of a year if they are rewashed.[92] We assume that if two cones are alternated in use over the course of the year, with 20 filtering sessions (from 20 boiling runs in S0,S1), 10 total washes need to take place in order to reuse them for the next season. Assuming an average of 625 Wh per washing cycle,[a] and air drying the cones after the fact would lead to gravity filtering having an electric energy input of 6.25 kWh over the course of the season.[140,141] No diatomaceous earth was assumed to be used when using cone filters.[142]

Filter presses were assumed to fall into the three size categories (7", 10", 20") based on the number of taps.[131] The amount of DE and filter paper needed over the course of the year was

[a] The European averages were used instead of the US average as the temperatures of the wash were provided, as well as to account for efficiency increases in US washing machines. European average was ~620 Wh which was close to US industry estimate 625 Wh.

determined based on guidelines from CDL.[132] The conservative estimate of precoat DE was taken at 2 lbs. per 10 sq. ft. of plate. Note that the calculations were based on a filter press with 10 plates, whereas the most common filter presses sold have six. Using the calculations from a 10-plate system allows for a conservative estimate and includes potential for mistakes made in the filtration process (papers and DE must be replaced if the pressure in the system reaches 60 psi). The total amount of DE and filter paper was multiplied by the number of runs over the course of the season to estimate the number of times filtering. It was assumed that syrup was filtered directly off the evaporator and did not need to be reheated to 185-195 °F before being filtered. The electricity used by the filter press was calculated using the viscous liquid estimate from CDL (5 gallons of syrup processed per square foot of plate per hour) with a 6-plate press. It was assumed that a diaphragm pump would be hooked up to a ⅓ hp motor,[143] which would run at full power while filtering, at a total operating efficiency equal to the electric vacuum pump and releaser (67.5%). The number of filtering sessions was assumed to be equal to the number of boils, with one minute of warm up time and one minute of cool down time for the pump at full rated power during each use. The total amount of time boiling multiplied by the power of the pump was then converted from hp-hrs. into kWh.

Heating needs were calculated based on the total volume of space needed to be heated in the sugarhouse and the total volume of hot water used to clean. The size of the sugarhouse was determined to be 320 sq. ft. for small operations, 432 sq. ft. for medium sized operations, and 560 sq. ft. for larger operations, with a standard ceiling height of 8 ft.[144] Heating degree days were calculated using a production weighted average (2022 production)[35] of heating degree days by region for 2018-2022.[145] It was assumed that the buildings were uninsulated, and a U value of 1.064 (plywood) was used for the heat loss coefficient (U).[146] The total amount of water heated from 40-120 °F was assumed to be two gallons of hot water per gallon of syrup produced. Based on trends in producer data, liquefied petroleum gas was modeled for both space and water heating, with a boiler efficiency of 84% and a furnace efficiency of 80%.[147,148]

Lighting was assumed using the guidance of Wells (1980), but updated for the improvement in efficiency of compact fluorescent bulbs (moving from 15W lightbulbs in 1980 to 20W bulbs in 2023).[144,149] It was assumed there was one bulb per 175 sq. ft., along with four exterior lights and three workstation lights within the sugarhouse.[144] It was assumed that all lights ran for six hours per day from October through May (243.25 days/yr. average).

Table S9: Archetype inventory for the processing stage. Information in this table is run through the LCA model to generate energy and emissions intensity for this stage.

		S0 wood	S0 oil	S1 wood	S1 oil	S2 wood	S2 oil	S3 wood	S3 oil	S4 wood	S4 oil	S5 wood	S5 oil	M0 Wood	M0 Oil	M1 Wood	M1 Oil	M2 Wood	M2 Oil	M3 Wood	M3 Oil	M4 Electric	L0 Oil	L1 Electric
Evaporators[56,119]	Evaporator Size	2' x 6'	2' x 6'	2' x 6'	2' x 6'	2' x 6'	2' x 6'	2' x 6'	2' x 6'	2' x 6'	2' x 6'	2' x 6'	2' x 6'	4' x 12'	4' x 12'	4' x 12'	4' x 12'	4' x 12'	4' x 12'	4' x 12'	4' x 12'	Master E	5' x 14'	Master E
	Fuel Type	Wood	Fuel Oil	Wood	Fuel Oil	Wood	Fuel Oil	Wood	Fuel Oil	Wood	Fuel Oil	Wood	Fuel Oil	Wood	Fuel Oil	Wood	Fuel Oil	Wood	Fuel Oil	Wood	Fuel Oil	Electric	Fuel Oil	Electric
	Fuel Amount (gal, cord, or kWh)	4.19	390.5	4.19	390.5	4.19	390.5	9.17	854.7	1.81	169.1	1.58	147.0	40.00	3728	4.70	438	10.29	958.6	8.95	833.6	1119.4	1780.2	3251.5
Steam Kettle	Fuel Amt (kWh)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1139.7	0	3310.7
Reverse Osmosis (RO)[124,130]	RO Model	0	0	0	0	0	0	0	0	Econox 600	Econox 600	Econox 600	Econox 600	0	0	Econox 1200	Econox 1200	Econox 1200	Econox 1200	Econox 1200	Econox 1200	Econox 2000	Econox 2000	Econox 2000
	# Posts / Process Rate	0	0	0	0	0	0	0	0	1 / 550 GPH	1 / 550 GPH	1 / 550 GPH	1 / 550 GPH	0	0	2 / 950 GPH	2 / 950 GPH	2 / 950 GPH	2 / 950 GPH	2 / 950 GPH	2 / 950 GPH	4 / 1600 GPH	6 / 2000 GPH	6 / 2000 GPH
	RO Fuel (kWh)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	164.72	164.72	164.72	164.72	0.00	0.00	665.85	665.85	1457.2	1457.2	1457.2	1457.2	1218.1	3014.3	3416.2
Filtering[92,132,150]	Filter Press Size	0	0	7"	7"	7"	7"	7"	7"	7"	7"	7"	7"	10"	10"	10"	10"	10"	10"	10"	10"	10"	20"	20"
	Filter Press Fuel (kWh)	0.00	0.00	3.69	3.69	3.69	3.69	7.78	7.78	7.78	7.78	7.78	7.78	16.42	16.42	16.42	16.42	35.56	35.56	35.56	35.56	35.56	25.97	25.97
	Filter Paper Size	0	0	7"	7"	7"	7"	7"	7"	7"	7"	7"	7"	10"	10"	10"	10"	10"	10"	10"	10"	10"	20"	20"
	Filter Paper Amount	0	0	400	400	400	400	400	400	400	400	400	400	500	500	500	500	500	500	500	500	500	600	600
	Gravity Filter Size	Small- 5 gal	Small- 5 gal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Filter Cones	2 x 8 qt	2 x 8 qt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Filter Cone Washing (kWh)	6.25	6.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Filter Racks	1 x 8 qt	1 x 8 qt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Cleaning Agents and Insulation[151,152]	Diatomaceous Earth (gal)	0.00	0.00	9.48	9.48	9.48	9.48	10.89	10.89	10.89	10.89	10.89	10.89	25.97	25.97	25.97	25.97	39.51	39.51	39.51	39.51	39.51	120.17	120.17
	Pan Cleaner (gal)	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	0.00	8.64	0.00
	Defoamer Non-organic (gal)	0.06	0.06	0.06	0.06	0.06	0.06	0.14	0.14	0.04	0.04	0.04	0.04	0.61	0.61	0.10	0.10	0.22	0.22	0.22	0.22	0.00	0.52	0.00
	Citric Acid (gal)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.83	0.83	0.83	0.83	0.00	0.00	2.08	2.08	2.08	2.08	2.08	2.08	4.17	7.50	7.50
	Glycol (gal)	0	0	0	0	0	0	0	0	1	1	1	1	0	0	2	2	2	2	2	2	4	6	6
	RO Soap (gal)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.08	0.08	0.08	0.00	0.00	0.20	0.20	0.20	0.20	0.20	0.20	0.39	0.70	0.70
Heating	Heating Fuel (gal LPG)	29.39	29.39	29.39	29.39	29.39	29.39	31.34	31.34	31.34	31.34	31.34	31.34	53.17	53.17	53.17	53.17	71.85	71.85	71.85	71.85	71.85	148.47	148.47
Lighting	Lighting Fuel (kWh)	193.28	193.28	193.28	193.28	193.28	193.28	193.28	193.28	193.28	193.28	193.28	193.28	207.29	207.29	207.29	207.29	207.29	207.29	207.29	207.29	207.29	223.30	223.30

Cleaning agent amounts were estimated based on cleaning schedules of specific equipment.[151,152] RO soap was calculated as 1 tbsp per post (membrane) per run. This assumes the number of times cleaning the RO corresponds to the number of boils. Glycol as a membrane preservative was calculated based on a one gallon per post ratio used at the end of the season. Citric acid was calculated from the ratio ⅔ cup per post per wash, assuming a washing schedule of once per run to prevent fouling. Membrane preservative was neglected, as it was specified at a ratio of 1 tsp. per membrane per season (when it is stored away). Defoamer was assumed to be 0.6 grams per 10 gallons of sap through the evaporator. Pan cleaner was calculated based on CDL washing guidelines for every three boils.[139] Calculations were made as 1 part pan cleaner to 100 parts water and assumed with a 2 inch column in the pan. The 2'x6' evaporator was cleaned the same as the 2-½'x5' evaporator that CDL manufactures. Pan cleaners and defoamer were not used in the electric evaporator archetypes, as they are self-contained units that do not require these agents for cleaning or boiling.[153]

Bottling

Using the USDA NASS statistics for the 2022 season, an analysis of the total amount of syrup sold in bulk versus containers was compared to total production by tap (59% of total syrup was sold in bulk).[35,57] It was assumed that the archetypal scales selling in bulk (55-gallon drums) would be dominated by medium and large-scale operations. The percentage of syrup sold at each size distribution (34% medium and 61% large) was used to give a weighted average equal to the 59% sold in bulk in 2022. It was assumed that 85% of production for large scale producers would be retailed/wholesaled in bulk and 15% in HDPE containers of sizes ranging from 3.4 oz. to one gallon (1.1% 3.4 oz, 3.8% half pint, 7.1%-pint, 2.3%-quart, 0.6% half gallon and 0.2% gallon). Extra 55-gallon containers were allocated to store 10% of the stock for future bottling. To equate the amount of syrup sold in bulk in 2023, 23% of all medium sized production was assumed to be sold in bulk. 30% of the stock was stored in these drums on top of retail, for future bottling. The remaining 77% that was retailed consisted of 5.8% 3.4 oz, 19.3% half pint, 36.6%-pint, 11.6%-quart, 3.1% half gallon and 0.8%-gallon containers. We assumed that all retail for small producers was in the form of retail containers and had this distribution: 7.5% 3.4oz., 25% half pint, 47.5%-pint, 15%-quart, 4% half gallon, 1% gallon. It was assumed ½ of the syrup would be bottled after filtering, and the other half would be stored in a 55-gallon drum, heated, and bottled later in the year. No syrup was sold in bulk for the small archetypes.

Table S10: Equipment inventory for bottling used to construct LCA model.

Equipment	Size (single unit)	Weight (kg/unit)	Units	Design Life	Notes & Assumptions
3.4 oz HDPE[154,155]	3.4 oz	0.023	kg	1 yr.	Assuming cap is included and same material as bottle (HDPE) Based on shipping weight listed on Anderson's Maple Syrup

1/2-pint HDPE	1/2 pint	0.037	kg	1 yr.	Assuming cap is included and same material as bottle (HDPE)
1 pint HDPE	1 pint	0.051	kg	1 yr.	Assuming cap is included and same material as bottle (HDPE)
1 quart HDPE	1 quart	0.091	kg	1 yr.	Assuming cap is included and same material as bottle (HDPE)
1/2-gallon HDPE	1/2 gal	0.125	kg	1 yr.	Assuming cap is included and same material as bottle (HDPE)
1 gallon HDPE	1 gal	0.236	kg	1 yr.	Assuming cap is included and same material as bottle (HDPE)
55-gallon drum HDPE[156,157]	55 gal	10.91	kg	10 yr.	Proxy: BayTec
Insulated Water Jacket[158–161]	5 gal	12.12	kg	10 yr.	Material: Stainless Steel Linear fit for weight (kg) based on capacity: 0.758x+8.33
Insulated Water Jacket	11 gal	16.67	kg	10 yr.	Material: Stainless Steel Linear fit for weight (kg) based on capacity: 0.758x+8.33
Insulated Water Jacket	37 gal	36.38	kg	10 yr.	Material: Stainless Steel Linear fit for weight (kg) based on capacity: 0.758x+8.33
Insulated Water Jacket	45 gal	42.44	kg	10 yr.	Material: Stainless Steel Linear fit for weight (kg) based on capacity: 0.758x+8.33
Pneumatic Bottling Unit[162,163]	Standard (see notes)	36.36	kg	10 yr.	Proxy: Vevor Bottling Unit

The size of the insulated water jacket used to bottle was sized according to the number of boils, with the volume corresponding to the amount of syrup that would be bottled during a single boil. Using the same method as with storage containers, the total volume had a maximum of 45 gallons. If the amount of syrup after a single boil exceeded 45 gal. the total syrup (gal) was divided by 45 gal. and rounded to the nearest unit. The corresponding weight for insulated water jackets was calculated using a linear fit described in table S9. The pneumatic bottling machine was assumed to operate at 7.41Wh per retail container (excluding 55-gal drums), which is about equal to using a 1 hp pump to fill up a bottle every 25 seconds on average at 67.5% total efficiency. Using the thermodynamic model described in Checkoway 2024a (Appendix B), it was calculated that 0.0343 gal of propane would be needed to heat a gallon of cold syrup to 195 °F from 41 °F on a stove (with a burner efficiency of 40%) (induction stove citation).[164] For a conservative estimate, it was assumed all syrup being bottled would need to be reheated.[56]

Table S11: Archetype inventory for bottling for small producers. Information in table fed through LCA model.

Bottling		S0 wood	S0 oil	S1 wood	S1 oil	S2 wood	S2 oil	S3 wood	S3 oil	S4 wood	S4 oil	S5 wood	S5 oil
Packaging	# 3.4 oz HDPE	270	270	270	270	270	270	590	590	590	590	590	590
	# 1/2-pint HDPE	382	382	382	382	382	382	836	836	836	836	836	836
	# 1-pint HDPE	363	363	363	363	363	363	795	795	795	795	795	795

	# 1-quart HDPE	58	58	58	58	58	58	126	126	126	126	126	126
	# 1/2-gallon HDPE	8	8	8	8	8	8	17	17	17	17	17	17
	# 1-gallon HDPE	1	1	1	1	1	1	3	3	3	3	3	3
	# 55-gallon drum HDPE	1	1	1	1	1	1	2	2	2	2	2	2
Equipment	Water Jacket Size (gal)	5	5	5	5	5	5	11	11	11	11	11	11
	Bottling Fuel (gal propane)[56]	3.27	3.27	3.27	3.27	3.27	3.27	7.16	7.16	7.16	7.16	7.16	7.16
	Pneumatic bottler fuel (kWh)	0.00	0.00	0.00	0.00	0.00	0.00	175.33	175.33	175.33	175.33	175.33	175.33

Table S12: Archetype inventory for bottling for medium and large producers. Information in table fed through LCA model.

Bottling		**M0 Wood**	**M0 Oil**	**M1 Wood**	**M1 Oil**	**M2 Wood**	**M2 Oil**	**M3 Wood**	**M3 Oil**	**M4 Electric**	**L0 Oil**	**L1 Electric**
Package	# 3.4 oz HDPE	1982	1982	1982	1982	4337	4337	4337	4337	4337	2454	2454
	# 1/2-pint HDPE	2808	2808	2808	2808	6144	6144	6144	6144	6144	3477	3477
	# 1-pint HDPE	2667	2667	2667	2667	5837	5837	5837	5837	5837	3303	3303
	# 1-quart HDPE	422	422	422	422	922	922	922	922	922	522	522
	# 1/2-gallon HDPE	57	57	57	57	123	123	123	123	123	70	70
	# 1-gallon HDPE	8	8	8	8	16	16	16	16	16	9	9
	# 55-gallon drum HDPE	9	9	9	9	20	20	20	20	20	101	101
Equip.	Water Jacket Size (gal)	37	37	37	37	2 x 45	2 x 45	2 x 45	2 x 45	2 x 45	5 x 45	5 x 45
	Bottling Propane (gal)[56]	31.24	31.24	31.24	31.24	68.36	68.36	68.36	68.36	68.36	198.57	198.57
	Bottler Fuel (kWh)	588.44	588.44	588.44	588.44	1287.33	1287.33	1287.33	1287.33	1287.33	728.52	728.52

Shipping Inflows and Distribution Outflows

While the distribution model was not directly included in the process flow defined in the main paper, distribution was calculated based on packaging and freight distance. Using EPA emissions estimates for heavy duty trucking and weighting them based on IPCC GWP 100 metrics, kg CO_2 per tonne-km was calculated for shipping by truck.[38,165]

Table S13: Packaging assumptions for national retail by heavy duty truck.[58] 55-gal containers do not require cases, but are bound four to a pallet.(cite master's project)

	3.4 oz	½ Pint	Pint	Quart	½ Gallon	Gallon
Bottles per case	48	12	12	6	6	4
Case weight (kg)[166]	0.053	0.053	0.071	0.101	0.089	0.101
Cases per pallet	70	70	66	48	40	36

We assume that there were two pallet straps per pallet each weighing 0.02 kg, and 1 lb. of LDPE wrapping.[58,167,168] The emissions burden of producing these materials was added to the shipping emissions associated with transporting the syrup. The density of syrup being transported was based on the regulated weight of 11.1382 lbs. per gallon (5.063 kg per gallon).

Emissions from shipping equipment to the sugarbush was calculated using the same emissions factor for heavy duty trucking. Total weight of equipment coming to the sugarbush was allocated based on total weight of the object divided by design life. Personal vehicles were assumed to be driven by the owner of the sugarbush and not shipped to the sugarbush. All solid and liquid fuels that could not be directly transported by the producer (diesel and gasoline) was assumed to be freighted based on the total volume consumed for that year and the density. Wood was assumed to be cut and dried on the premises of the sugarbush. Fuel transportation assumption can be found in the materials and fuels section of Appendix A.

Solid waste was assumed to include all agricultural plastics (tubing and taps), all other parts of the tubing system (stainless steel wire and clamps), filter paper, filter cake, plastic bottles used for packaging syrup, and packaging used for retail (pallet wrap, bands, cardboard). Due to a lack of data surrounding filter cake, they were calculated as the amount of diatomaceous earth in the system, which is the low-end value of what a filter cake would weigh. Niter would also be considered solid waste, but there is a lack of data regarding the quantity as this varies producer to producer.

Materials and Fuels

A large portion of the data for upstream and downstream impacts of material and fuel production were sourced from GREET 2022 by Argonne National Laboratory.[37] The next section (GREET Assumptions) is the set of considerations made when exercising the GREET model for data. All considerations not described below were left as the GREET 2022 defaults when running the model.

GREET Assumptions

This section details the specific choices made when setting up the parameters of the GREET model in GREET 1. The headers and numbers represent sections with parameters that can be toggled in the Input Tab of GREET 1 before running the results in the model. The same parameters are linked into GREET 2:

Target Year For simulation– [2023] (vehicles were modeled based on the average fleet age year in GREET, all electricity, material, and fuel production were modeled using the target year)[169]

Petroleum–
3.1.a) [1] EIA projection of crude oil share output
3.3.a) [0] time series default
3.4.a) [1] ethanol blended by volume.[170]
3.5.b) [US not CA gasoline]

Natural Gas–
4.1) [1] across the board, North American NG is more common in rural communities than renewable natural gas
4.3) [2] EPA defined leakage as they have tighter regulations on GHG emissions and therefore more accurate projections
4.6) [No] NG infrastructure is minimal in the overall emissions and energy from transportation and combustion

Electric Generation–
10.1) [2] Emissions factors based on EPA and EIA database in g/kWh
10.2.a) selection is dependent on region but for vehicles we are using mix for transportation use and changing it to the region in which the sugarbush is located. The use of the vehicle will be within the operation itself so it will most likely remain within the state grid (for any electric vehicle charging). Any stationary use would also occur here, so this assumption is more specific to the location of the sugarbush.
10.6) [No] infrastructure of power plant is not nearly as much as combustion
10.7) [1] Dependent on mix selected in section {10.2.a}

PHEV–
12.3.a) ranges PHEV [40] and BEV [300] because those are good approximations of plug-in range parameter in 2023.

Well to Pump–
13.1) [80.0%] this is a good approximation across a wider range of generation capacities. Anything between 80-85% seems reasonable.[171]

There also were adjustments made inside of the GREET model when extracting data as well, namely a correction in the losses from nuclear fuel and the use of higher heating value (HHV) rather than the default lower heating value (LHV). HHV was used to capture the total fuel resource being used, even if all heat was not being recovered for energy. GREET began as a transportation model, where the convention is LHV, but it breaks down when HHV is selected for calculations as not every fuel has a well-defined HHV. To adjust for this breakdown, fuels with HHVs were used in calculations when available, and fuels that only had LHVs used those as a placeholder. This was determined to be a reasonable simplification for the purposes of this work because the fuels that did not have an HHV are not commonly used in electricity production, fuel production, or the maple industry at all, and would have very little effect on the results coming out of GREET.

The nuclear correction was also assumed to have little impact on the emissions and energy data from the combustion and production of fuels and materials but was used in state-by-state electricity that was sourced from GREET. GREET reports the primary energy of electricity to be 2.0 MJ of energy per MJ of generated electricity, which does not fully account for nuclear power plant losses (assigning only 0.21 MJ primary energy to 19% of total generation-share contributed by nuclear). To account for this, the NREL LCI database was used to assign a primary energy of 3.11 MJ of energy per MJ of nuclear electricity generated, resulting in a total primary energy for US electricity of 2.45 MJ per MJ of electricity, an efficiency of 40.8%.[172]

GHG emissions were calculated based on the total emissions of CO_2, N_2O, and CH_4. This total was then weighted based on IPCC AR6 GWP 100 emissions factors for gaseous compounds.[40] CO_2 was calculated using the carbon fractions in VOC and CO as well as the total amount of CO_2 emitted. The carbon fractions were taken from GREET, with VOC and CO having a carbon fraction of 0.85 and 0.43 respectively.

Table S14: Production energy and emissions for materials used in the carbon footprinting model. Plastics are combined production unless otherwise specified i.e., extruded. Combine production plastics were used for modeling of non-vehicle materials within the carbon footprinting model.

Material	Density (kg/m3)[173]	Energy (MJ/kg product)	Emissions (kgCO_2e /kg product)	Source:
HDPE	960	77.69	1.83	GREET
LDPE	910	84.01	2.13	GREET
PET	935	75.17	2.18	GREET
Polypropylene	925	74.96	1.56	GREET
Polycarbonate	1200	115.26	4.79	GREET
PVC	1410	58.51	2.42	GREET
HDPE extruded	960	65.57	1.04	GREET
LDPE extruded	910	71.55	1.33	GREET
PVC extruded	1410	54.98	2.03	GREET
PP extruded	925	66.75	1.04	GREET
PC extruded	1200	101.89	3.97	GREET

Nylon	1140	135.49	6.67	GREET
AVG Plastic	1057	86.92	3.27	GREET
Rubber	1100	54.77	3.56	GREET
Glass[44]	2600	16.60	1.25	See Reference
Aluminum	2700	123.18	7.60	GREET
Stainless Steel	7735	13.85	0.82	GREET
Cast Iron	7200	31.94	0.86	GREET
Polyester[42]	1200	95.00	5.80	See Reference
Refractory Cement[43]	1810	8.40	0.70	See Reference
Refractory Brick[43]	2403	13.00	1.10	See Reference
Fiberglass Insulation	16	12.13	0.77	GREET
Galvanized Steel	7800	34.72	3.09	GREET

Fuels

Data for all liquid fuels were sourced from both GREET and the 2023 EPA fuel combustion emissions inventory. Upstream emissions were sourced from fuel production in GREET. Energy factors were taken as the primary energy ratio listed in GREET [mmbtu/mmbtu]. The EPA inventory uses LHV, so all values were scaled based on HHV. Diesel and no 2. fuel oil were assumed to be the same. Chainsaw Premix was constructed as 50 parts gasoline to 1 part fuel oil.[174]

Table S15: Stationary combustion fuel properties table. Wood was assumed to have upstream energy and emissions covered by activities performed on site in the scenarios. The density of propane was calculated based on the weight of a 20 lb. tank and *was used for the purposes of determining the transportation energy of freighting those tanks.*

Fuel Type	Fuel Unit	Upstream Energy Factor	HHV Combustion (BTU / unit fuel)	Upstream Emissions (kg/mmbtu)	Combustion Emissions (kg/mmbtu)	LHV/HHV Ratio	TFC Energy (MJ per unit fuel)	TFC Emissions (kgCO_2e/ MJ)	Density (kg/unit fuel)[81]
Fuel Oil	gal	1.12	138000	7.61	74.21	0.93	162.76	0.08	3.31
Gasoline	gal	1.21	125000	15.27	70.47	0.93	159.65	0.08	2.83
Diesel	gal	1.12	138000	7.61	74.21	0.93	162.76	0.08	3.31
Propane	gal	1.13	91000	10.48	61.71	0.92	108.82	0.07	1.98[175]
LPG	gal	1.14	92000	11.07	61.96	0.93	110.83	0.07	2.09[148]
Softwood	cord	--	19897572	--	95.00	--	20991.94	0.09	1305.00
Hardwood	cord	--	27041400	--	95.00	--	28528.68	0.09	1395.63
Chainsaw Premix	gal	1.21	125255	15.12	70.55	0.93	159.73	0.08	2.84
Chainsaw Bar Oil	gal	1.12	144000	7.61	74.52	--	169.84	0.08	3.31

Chainsaw bar oil was modeled as a lubricant from the EPA tables but assumed to have upstream impacts like fuel oil and diesel. The heating value of bar oil was kept as the EPA table default LHV. Densities of individual fuels were taken from their physical properties. The densities themselves were used to calculate transportation burdens for fuels delivered directly to the sugarbush.

Wood combustion data were sourced from the University of Missouri Extension[176] and EPA tables. Energy was calculated based on air dried hardwood and softwood at 20% moisture content. Emissions for hardwood and softwood were assumed to be the same as per the EPA tables.

Mobile combustion factors were used to determine emissions from fuels used in recreational vehicles (UTV, ATV, & snowmobile) and in agricultural vehicles (tractors). The same method was used as with stationary, where upstream impacts were sourced from GREET while downstream impacts were sourced from the EPA guidelines.

Table S16: Mobile combustion properties table for different fuels and vehicle types used in sap collection. Note that this is a slightly higher estimation, as it uses TFC energy rat5her than combustion energy for emissions. This estimate is reasonable, as many producers use older tractors with higher use emissions than current averages.

Mobile Combustion Rec Vehicles[39]	HHV MJ/gal	GHG kg CO_2 e/gal	Upstream Emissions (kg CO_2 e /MJ)	Upstream Energy Factor	LHV/HHV Ratio	TFC Energy (MJ/gal)	TFC Emissions (kg CO_2e/gal)
Gasoline (2 stroke)	131.88	9.33	0.02	1.22	0.93	161.15	11.86
Gasoline (4 stroke)	131.88	9.28	0.01	1.20	0.93	157.86	11.56
Diesel	145.59	10.40	0.01	1.12	0.93	162.81	11.66

Mobile combustion Ag Equipment	HHV MJ/gal	GHG kg CO_2 e/gal	Upstream Emissions (kg CO_2 e /MJ)	Upstream Energy Factor	LHV/HHV Ratio	TFC Energy (MJ/gal)	TFC Emissions (kg CO_2e/gal)
Gasoline (2 stroke)	131.88	9.11	0.01	1.21	0.93	159.65	11.42
Gasoline (4 stroke)	131.88	9.17	0.01	1.19	0.93	157.44	11.44
Diesel	145.59	10.54	0.01	1.12	0.93	162.76	11.71

Results

This section contains figures and tables referenced in the main text. See the main text for the context, description, and comparison with similar figures and tables.

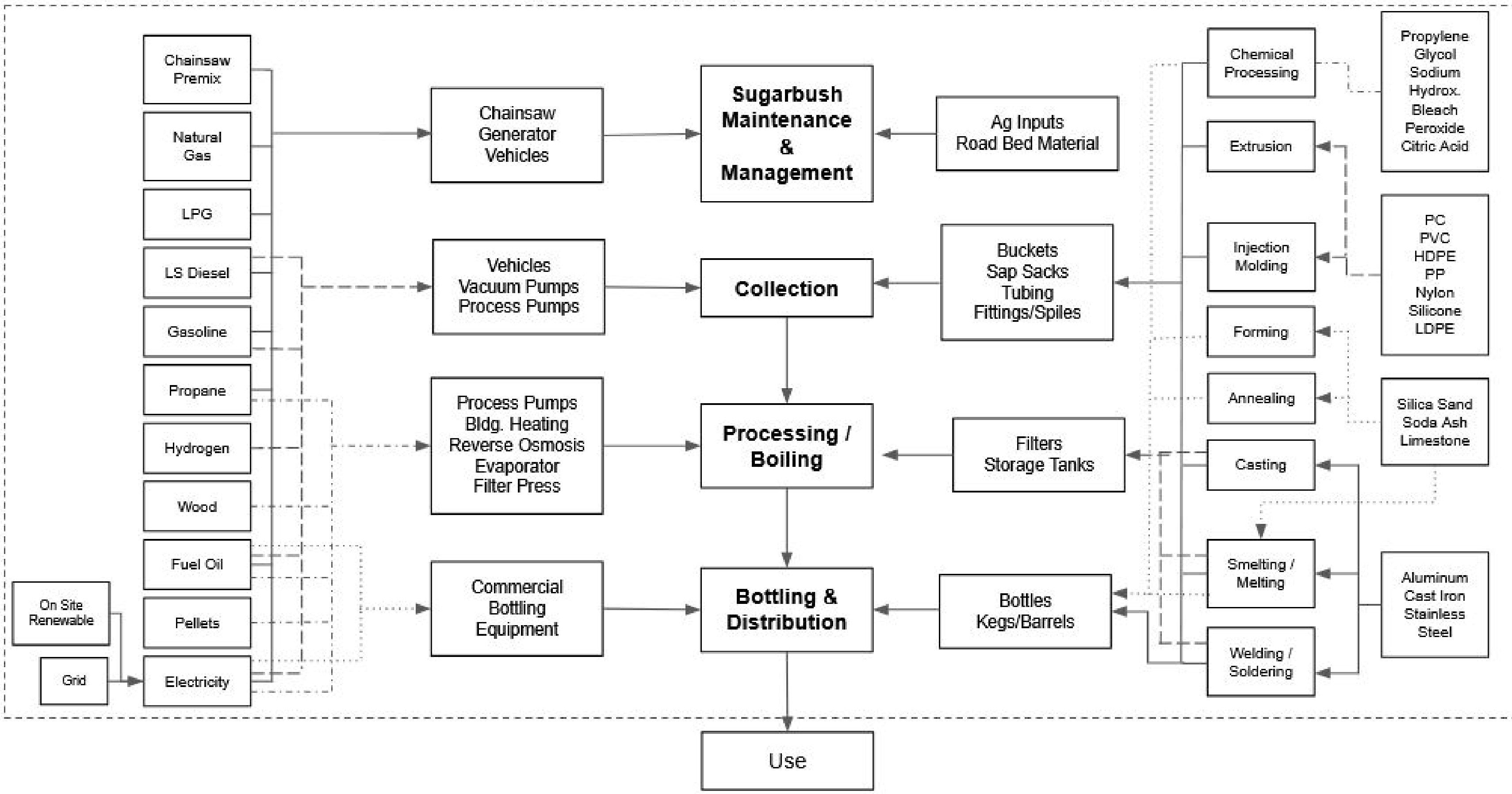


Figure S4 Sap to syrup Process Model block diagram, process stages are outlined in bold, dashed line is the system boundary for this analysis.

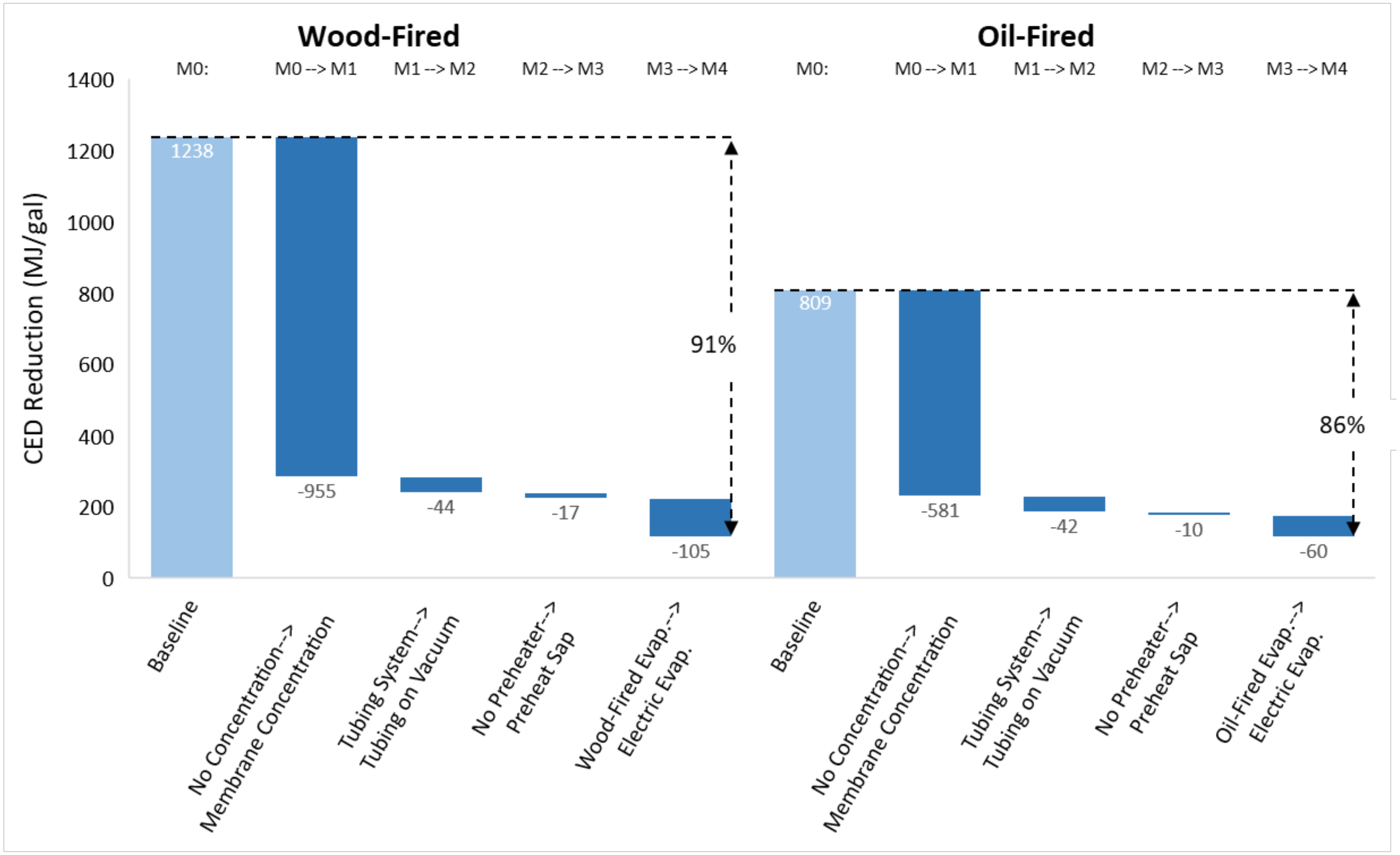


Figure S5: Left) Energy reduction by process change for medium sized producers using wood as the evaporator fuel. Right) Energy reduction by process change for medium sized producers using fuel oil as the evaporator fuel. The baseline case is the same for both fuels (no RO, no vacuum pumps, no preheater, non-electric evaporator).

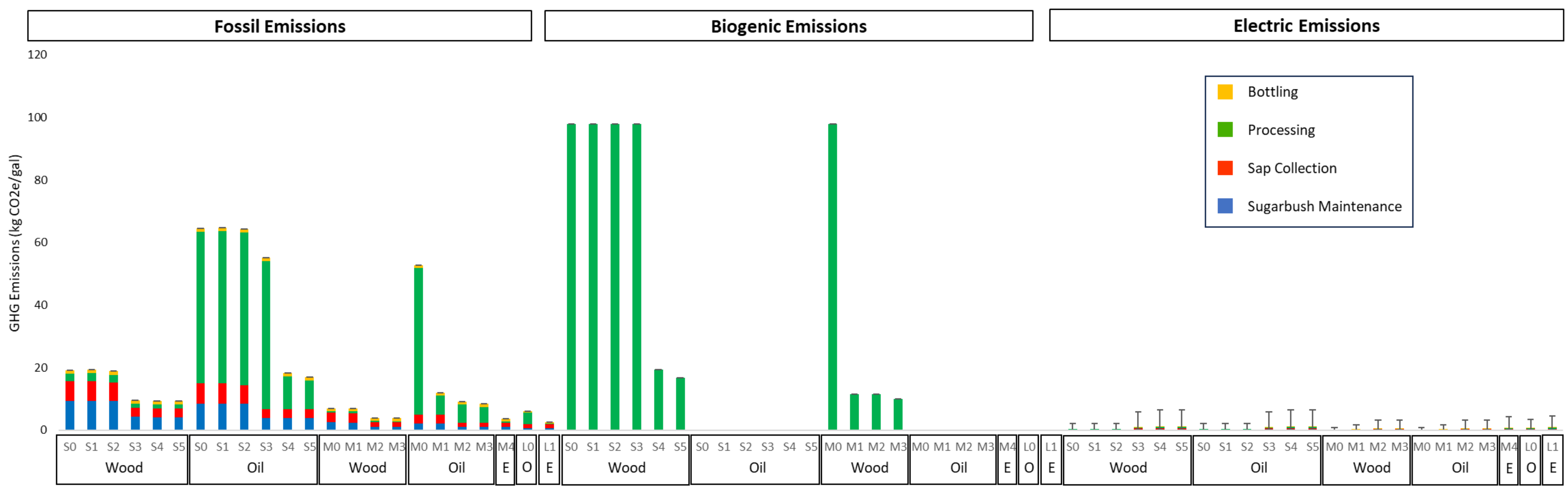


Figure S6: GHG emissions broken down by process step and emissions type for each production archetype. Error bars represent variability in electric emissions based on geography, with the average being the 2022 production weighted average of the 13 NAMSC state grids (0.18 kg kWh), the low being VT (0.02 kg/kWh), and the high being WV (1.02 kg/kWh).

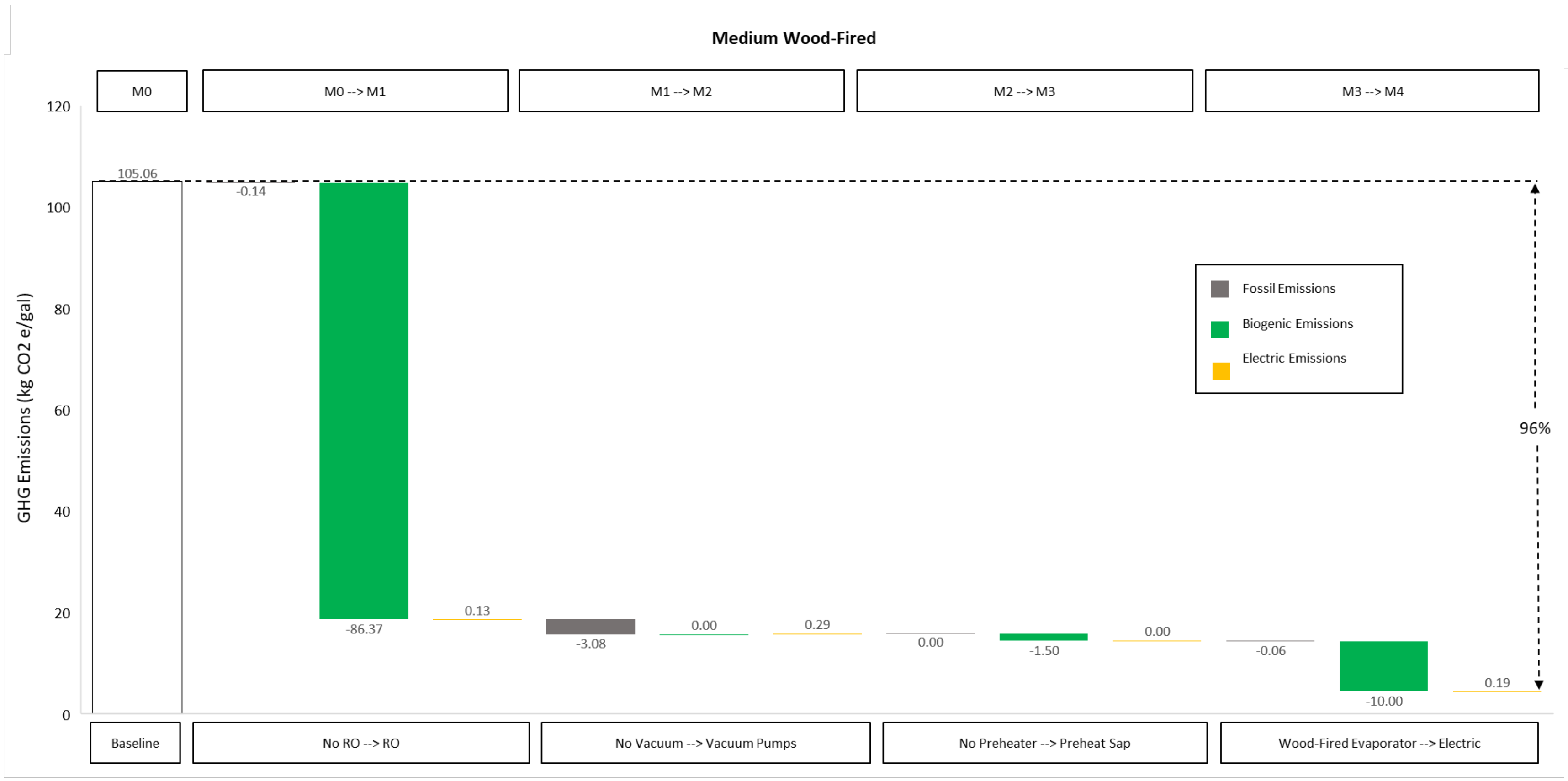


Figure 7: Emissions reduction by process change for medium producers using wood as the evaporator fuel. Reductions for each emission type (fossil, biogenic, electric) are isolated with respect to the baseline case (no RO, no vacuum pumps, no preheater, wood-fired evaporator). All emissions are represented in a NAMSC 2022 production weighted average electric grid (0.18 kg/kWh).

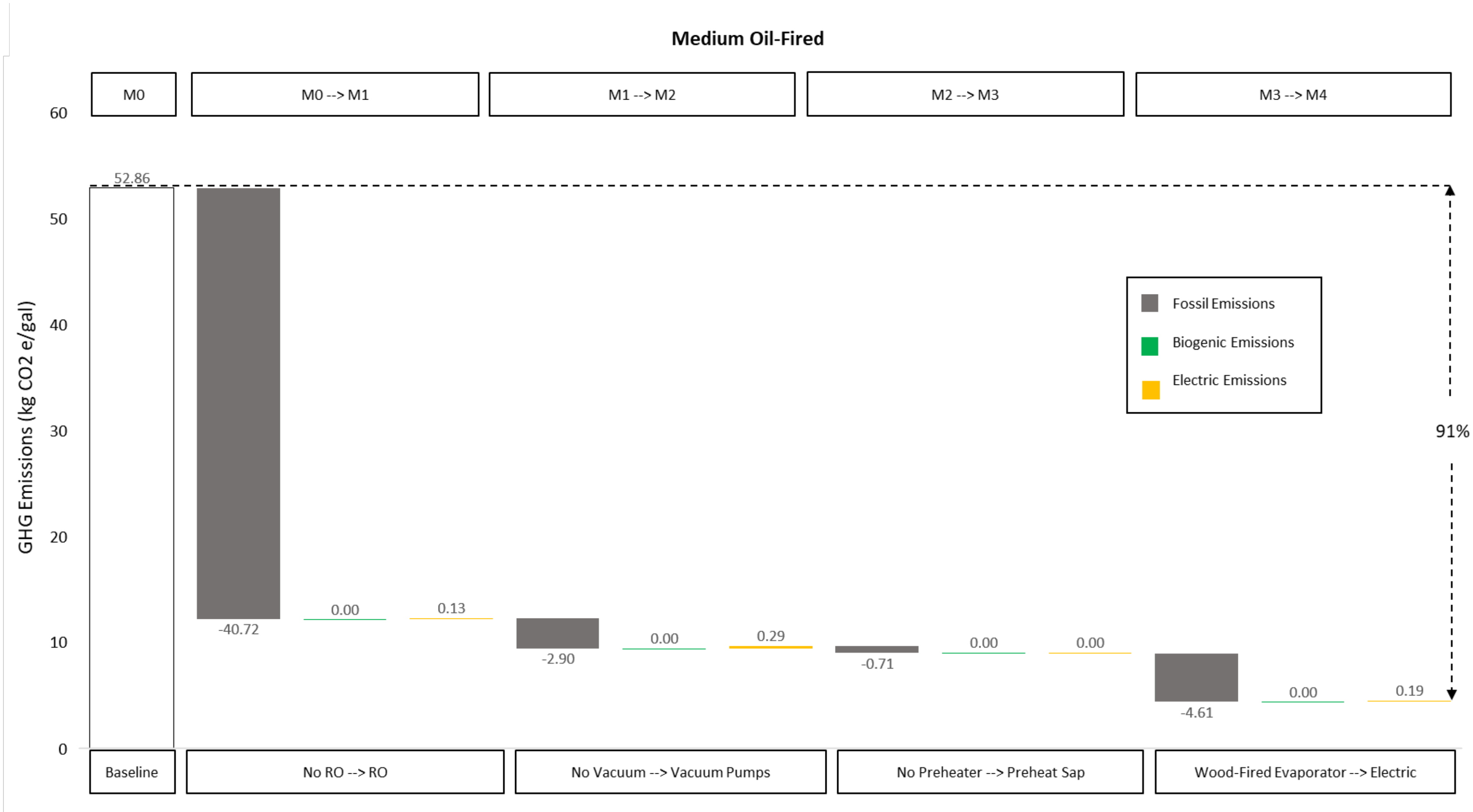


Figure S8: Emissions reduction by process change for medium producers using fuel oil as the evaporator fuel. Reductions for each emission type (fossil & electric) are isolated with respect to the baseline case (no RO, no vacuum pumps, no preheater, oil-fired evaporator). All emissions are represented in a NAMSC 2022 production weighted averaged electric grid.

Table S17: Solid waste and its embodied carbon for each archetype. The right two columns are the total waste and embodied carbon normalized according to the functional unit and scaled based on the other archetypes.

Archetype	Maple Syrup Produced (gal)	Solid Waste (kg)	Embodied Carbon (kg CO2e)	Waste (kg/gal)	Embodied Carbon (kg CO2e/gal)
S0 wood	95.48	59.11	100.61	0.62	1.05
S1 wood	95.48	78.86	111.93	0.83	1.17
S2 wood	95.48	121.62	223.36	1.27	2.34
S3 wood	208.96	186.15	332.34	0.89	1.59
S4 wood	208.96	186.15	332.34	0.89	1.59
S5 wood	208.96	186.15	332.34	0.89	1.59
S0 oil	95.48	59.11	100.61	0.62	1.05
S1 oil	95.48	78.86	111.93	0.83	1.17
S2 oil	95.48	121.62	223.36	1.27	2.34
S3 oil	208.96	186.15	332.34	0.89	1.59
S4 oil	208.96	186.15	332.34	0.89	1.59
S5 oil	208.96	186.15	332.34	0.89	1.59
M0 Wood	911.38	949.45	1915.18	1.04	2.10
M1 Wood	911.38	949.45	1915.18	1.04	2.10
M2 Wood	1994.59	1432.98	2722.23	0.72	1.36
M3 Wood	1994.59	1432.98	2722.23	0.72	1.36
M0 Oil	911.38	949.45	1915.18	1.04	2.10
M1 Oil	911.38	949.45	1915.18	1.04	2.10
M2 Oil	1994.59	1432.98	2722.23	0.72	1.36
M3 Oil	1994.59	1432.98	2722.23	0.72	1.36
M4 Electric	1994.59	1432.98	2722.23	0.72	1.36
L0 Oil	5793.80	2570.23	5148.72	0.44	0.89
L1 Electric	5793.80	2570.23	5148.72	0.44	0.89

Table S18 Annual solid waste and embodied carbon breakdown by category for each archetype. Normalized waste and emissions are scaled based on the other archetypes. Fossil % represents the fraction of fossil emissions for producing a gallon of syrup as embodied carbon in solid waste.

	S0 Wood	***S1 Wood***	***S2 Wood***	***S3 Wood***	***S4 Wood***	***S5 Wood***	***S0 Oil***	***S1 Oil***	***S2 Oil***	***S3 Oil***	***S4 Oil***	***S5 Oil***
Maple Syrup (gal)	95	95	95	209	209	209	95	95	95	209	209	209
Tubing system (kg)	6.52	6.52	49.28	49.28	49.28	49.28	6.52	6.52	49.28	49.28	49.28	49.28
Tubing (kg CO_2e)	8.08	8.08	119.51	119.51	119.51	119.51	8.08	8.08	119.51	119.51	119.51	119.51
Bottles (kg)	46.41	46.41	46.41	101.41	101.41	101.41	46.41	46.41	46.41	101.41	101.41	101.41
Bottles (kg CO_2e)	84.73	84.73	84.73	185.16	185.16	185.16	84.73	84.73	84.73	185.16	185.16	185.16
Packaging (kg)	6.15	6.15	6.15	13.00	13.00	13.00	6.15	6.15	6.15	13.00	13.00	13.00
Packaging (kg CO_2e)	7.62	7.62	7.62	16.11	16.11	16.11	7.62	7.62	7.62	16.11	16.11	16.11
Filter cake (kg)	0.00	17.86	17.86	20.54	20.54	20.54	0.00	17.86	17.86	20.54	20.54	20.54
Filter cake (kg CO_2e)	0.00	0.40	0.40	0.45	0.45	0.45	0.00	0.40	0.40	0.45	0.45	0.45
Filter paper (kg)	0.03	1.91	1.91	1.91	1.91	1.91	0.03	1.91	1.91	1.91	1.91	1.91
Filter paper (kg CO_2e)	0.17	11.11	11.11	11.11	11.11	11.11	0.17	11.11	11.11	11.11	11.11	11.11
Total Solid Waste (kg)	59.11	78.86	121.62	186.15	186.15	186.15	59.11	78.86	121.62	186.15	186.15	186.15
Total Solid Waste (kg/gal)	0.62	0.83	1.27	0.89	0.89	0.89	0.62	0.83	1.27	0.89	0.89	0.89
Total Embodied Carbon (TEC) (kg CO_2e)	100.61	111.93	223.36	332.34	332.34	332.34	100.61	111.93	223.36	332.34	332.34	332.34
TEC (kg CO_2e/gal)	1.05	1.17	2.34	1.59	1.59	1.59	1.05	1.17	2.34	1.59	1.59	1.59
Fossil Fraction	5%	6%	12%	17%	17%	17%	2%	2%	4%	3%	9%	9%

	M0 Wood	***M1 Wood***	***M2 Wood***	***M3 Wood***	***M0 Oil***	***M1 Oil***	***M2 Oil***	***M3 Oil***	***M4 Electric***	***L0 Oil***	***L1 Electric***
Maple Syrup (gal)	911	911	1995	1995	911	911	1995	1995	1995	5794	5794
Tubing system (kg)	509.56	509.56	509.56	509.56	509.56	509.56	509.56	509.56	509.56	1733.96	1733.96
Tubing (kg CO_2e)	1206.12	1206.12	1206.12	1206.12	1206.12	1206.12	1206.12	1206.12	1206.12	3965.65	3965.65
Bottles (kg)	342.32	342.32	748.74	748.74	342.32	342.32	748.74	748.74	748.74	521.60	521.60
Bottles (kg CO_2e)	625.05	625.05	1367.14	1367.14	625.05	625.05	1367.14	1367.14	1367.14	952.39	952.39
Packaging (kg)	43.73	43.73	95.31	95.31	43.73	43.73	95.31	95.31	95.31	64.67	64.67
Packaging (kg CO_2e)	54.58	54.58	118.98	118.98	54.58	54.58	118.98	118.98	118.98	89.64	89.64
Filter cake (kg)	48.95	48.95	74.48	74.48	48.95	48.95	74.48	74.48	74.48	226.54	226.54
Filter cake (kg CO_2e)	1.08	1.08	1.65	1.65	1.08	1.08	1.65	1.65	1.65	5.02	5.02
Filter paper (kg)	4.89	4.89	4.89	4.89	4.89	4.89	4.89	4.89	4.89	23.45	23.45
Filter paper (kg CO_2e)	28.34	28.34	28.34	28.34	28.34	28.34	28.34	28.34	28.34	136.03	136.03
Total Solid Waste (kg)	949.45	949.45	1432.98	1432.98	949.45	949.45	1432.98	1432.98	1432.98	2570.23	2570.23
Total Solid Waste (kg/gal)	1.04	1.04	0.72	0.72	1.04	1.04	0.72	0.72	0.72	0.44	0.44
Total Embodied Carbon (TEC) (kg CO_2e)	1915.18	1915.18	2722.23	2722.23	1915.18	1915.18	2722.23	2722.23	2722.23	5148.72	5148.72
TEC (kg CO_2e/gal)	2.10	2.10	1.36	1.36	2.10	2.10	1.36	1.36	1.36	0.89	0.89
Fossil Fraction	30%	30%	35%	35%	4%	17%	15%	16%	36%	15%	34%

Appendix B: Thermodynamic Model

Introduction

Running a successful maple syrup operation requires attention to detail, specifically with regards to production efficiency. Despite new technology and the innovation of new production methods, the amount of energy it takes to bring sap to the sugar concentration (measured as degrees Brix or °Bx) for maple syrup remains constant. The rule of thumb used to help sugar makers estimate their fuel costs was that it takes 400,000 BTU to bring 2 °Bx sap into maple syrup.[177] This rule of thumb is a close estimate, but it neglects the change in boiling point as the solution becomes more concentrated. Additionally, the amount of energy required to boil changes depending on the final concentration of syrup.[6] The thermodynamic model of the sap boiling process presented here accounts for changes in the composition of the solution as it undergoes boiling, resulting in a difference in energy of +5%, +3%, and +1% for 68, 67, and 66 °Bx syrup respectively. These differences are important for all sugar makers, as they also directly affect the cost of fuel per gallon of syrup for all fuel types. This model can be used by sugarmakers when calculating how much fuel they would need at different levels of concentration and with different fuel types to assess costs associated with producing maple syrup.

Thermodynamic Model

Sap is composed mainly of sucrose and water.[178] The remaining solids represent a negligible fraction of the composition of sap when it comes out of the tree, allowing sap to be treated as an ideal solution of sugar and water. In a standard season across the maple producing geographies of North America, the average initial sugar content of sap leaving the tree is 2 °Bx. From Sokolovsky (1958, p. 19),[179] the empirical approximation of the boiling point of sucrose-water solutions is:

$$T(°C) = 100\ °C + 2.33(S\ /\ W) \qquad \textit{(eqn. 1)}$$

where S is the concentration of sucrose in solution and W is the concentration of water. For high concentrations of sucrose, like we see in syrup, the boiling point approaches 105 °C.[180] As the composition of the solution changes with concentration, so does the specific heat capacity, which is directly proportional to mass:

$$Cp = (m\ \Delta T)\ /\ Q \qquad \textit{(eqn. 2)}$$

This relationship was quantified empirically by Sokolovsky (1958, p.32):[179]

$$Cp = 1 - (0.6 - 0.0018t)S \quad \textit{(eqn. 3)}$$

where t is the temperature of the solution (in this case the boiling point) for any given concentration S.

The energy supplied to the system to bring it to a boil and have the water evaporate into steam (therefore increasing the overall concentration of sugar in the solution) can be broken into two physical properties of the system: Q_{boil} and $Q_{vaporization}$. The first energy, Q_{boil}, was encountered above in the relation of specific heat capacity and represents the amount of energy needed to bring the solution to its boiling point from some initial temperature (ΔT) based on the amount of solution being heated (m) and the bulk physical properties of the solution that allow for the transfer of heat and subsequent increase in temperature (C_p). The second energy is the internal energy of the system that allows for a phase change:

$$Q_{vaporization} = mL_v = mH_v$$

where L_v is the latent heat of vaporization.[181] L_v is a physical property (also known as the enthalpy of vaporization H_v) that is essentially the energy needed to overcome the internal molecular forces constraining the kinetic degrees of freedom from one phase of matter to another.[182] Because the pressure tends to remain constant at the instant of a liquid-gas phase change, the change in the Gibbs' free energy ΔG is zero, meaning there is no pressure-volume work done through boiling the sucrose-water solution (an isobaric process) and is in equilibrium at that instant.[183]

$$\Delta G = \Delta H - T\Delta S = 0, \;\; \Delta H = T\Delta S = TdS \quad \textit{(eqn. 4)}$$

Substituting this case into Maxwell's thermodynamic relations we can see that enthalpy H is directly related to energy:[182]

$$dU = TdS - PdV = dH - PdV \quad \textit{(eqn. 5)}$$

$$\Delta H_v = \sum(\Delta U + P\Delta V) = \frac{Q_{vaporization}}{m} \quad \textit{(eqn. 6)}$$

where U is the internal energy of some amount of the system (energy per unit mass), P is the pressure, and V is the volume. Thus, allowing us to see what properties of the solution *(U, P, V)* make up $Q_{vaporization}$ for the bulk system.

Calculating the enthalpy of vaporization requires that one knows the pressure of the solution as it undergoes a phase change, also known as the vapor pressure.[184] As stated above, sugar-water solutions are considered ideal solutions. They are ideal because sucrose completely dissolves in water, meaning that the forces between the sucrose and the water are equal to the forces between the water molecules themselves, allowing for the same amount of energy to be needed to evaporate water from the surface during a phase change as if it was purely water.[184,185] Additionally, the activity of sucrose is equal to the concentration in an ideal solution, meaning the sucrose-sucrose interactions are negligible in solution. Sucrose is a non-volatile compound, meaning that it does not vaporize easily due to strong intramolecular forces.[186] It is important to note that the non-volatility of sucrose and the ideal nature of the solution is what was used in the rule of thumb for total energy needed to boil sap into a gallon of syrup. Due to these properties, the vapor pressures of different concentrations of sap and syrup can be calculated using Raoult's Law:[185,187,188]

$$P_{solution} = X_{solvent}\, P_{solvent} \quad \textit{(eqn. 7)}$$

where $X_{solvent}$ is the molar fraction of water in the sap. For water, the pressure of vaporization above 100 °C is non-linear and can be approximated as a function of temperature (in °C):[189]

$$P_{solvent} = 2427.9 - 60.726\,T + 0.44048\,T^2 \quad \textit{(eqn. 8)}$$

This approximation becomes necessary as the boiling point increases past the boiling point of pure water. As you can see from the relation above, the vapor pressure of the solution $P_{solution}$ continues to decrease as the sugar concentration of the solution increases as it is directly proportional to the decreasing molar fraction of water in the solution.

Using the vapor pressure and boiling point as the pressure and temperature constants at the point of phase change, one can use the Clausius-Clapeyron relation (eqn. 9) to determine the enthalpy of vaporization (H_v, in units of Joules per mol (J/mol)):[182,190,191]

$$ln\,(P_1/P_2) = (-\Delta H_v\,/\,R)(1/T_1 - 1/T_2) \quad \textit{(eqn. 9)}$$

where P_1 is the vapor pressure of sap at initial temperature T_1 = 40 °F (4.44 °C), and P_2 is the vapor pressure at the boiling point (T_2) calculated at each concentration of sucrose. To obtain enthalpy of vaporization in units of Joules per kilogram, the weighted molality of the solution at each concentration is multiplied by the enthalpy of vaporization found in eqn. 9. The weighted molality is calculated by multiplying the molar fraction of each part of the solution times its respective molality to get mass (m).

We now have our change in enthalpy of vaporization based on known physical properties of the system--concentration (°Bx), which is used to determine partial pressure, and temperature (°C). We can now use the change in enthalpy to create a discrete sum as the solution increases in concentration (one °Bx at a time). However, we also need to know how much mass is being lost as it boils and becomes more concentrated. We now need to figure out how many gallons of sap are needed to produce one gallon of finished syrup.

Modified Jones Rule of 86

Each physical property (enthalpy (H_v), vapor pressures (P_1 and P_2), boiling temperature (T_2), and sucrose concentration (X)) was calculated on a discrete basis between 2 and 68 °Bx with a ΔX of 1 °Bx. To accurately estimate the amount of energy required to boil, one must also consider the change in mass of the solution as water is evaporated. The other major rule of thumb in the sugar making community is the Jones Rule of 86, based on the 1946 paper by C.H. Jones, which approximated the amount of sap necessary to create one gallon of 65.5 °Bx syrup based on the starting Brix of sap. This rule was to take the number 86 and divide it by the starting Brix to obtain gallons of sap.[6,192] However, as recent modifications to the rule have pointed out, syrup can be anywhere from 66 to 68.9 °Bx to be considered legal.[193]

To reconcile this, a physical rule was derived for the loss of mass as sap undergoes boiling. Because sucrose is a non-volatile compound, the amount of sucrose (in terms of mass) stays constant while the amount of water decreases, which leads to the concentration increase. Knowing this, one can take the density of finished syrup (~1333 kg/m^3 or ~5 kg/gal at 68 °Bx) and multiply it by the percent sugar content of the syrup (°Bx/100) to find out the mass of sugar in one gallon of syrup. Because this number remains constant through boiling, the initial amount of sap needed can be calculated as the mass of sucrose divided by the density of the sap coming out of the tree. This results in a final relationship:

$$\#\ Gallons\ sap\ per\ Gallon\ Syrup = \frac{(X_f\, m_f)}{(X_i\ \rho_i)} \qquad \textit{(eqn. 10)}$$

where m_f is the density of finished syrup times one gallon, X_f and X_i are the final and initial concentrations of sucrose in solution respectively, and ρ_i is the density of amorphous sucrose, allowing for the dimensionless relationship:

$$\#\ Gallons\ sap\ per\ Gallon\ Syrup = \frac{(X_f\, \rho_f)}{(X_i\ \rho_i)} \qquad \textit{(eqn. 11)}$$

to yield the same result. As most sugarmakers use a hydrometer regularly to check the density of their syrup, one can always know how many gallons of sap they would need at any combination of input and output °Bx. It should be noted that the density of sugar solutions do not vary linearly with concentration as one would expect, because as sucrose crystallizes from its original amorphous form, its density changes with its physical structure. Using the starting and ending states that sucrose ends up in solution, we can approximate this linearly based on the range of densities (1507.7 kg/m^3 – 1586.2 kg/m^3). Empirically, eqn. 11 can be rewritten using only starting and ending °Bx concentrations:

$$\#\ Gallons\ sap\ per\ Gallon\ Syrup = \frac{(-3.384)*10^{-3}*X_i*X_f+1.017\ X_f}{(-3.714)*10^{-3}*X_i*X_f+1.017\ X_f} \qquad \textit{(eqn. 12)}$$

Using this ratio on a discrete basis allows for an accurate calculation of the decrease in water weight as you boil down 1 °Bx at a time. Using physcial properties of water and sucrose,[186,194–199] the mass of solution that remains after it is concentrated on a °Bx by °Bx basis was calculated to determine the energy needed to bring it to its next boiling point Q_{boil} and the energy expended in vaporizing that mass of water $Q_{vaporization}$.

$$Q_{boil} = \sum_{Ti}^{Tf} m\ Cp\ \Delta T \qquad \textit{(eqn. 13)}$$

$$Q_{vaporization} = \sum_{mi}^{mf} \Delta m\ Hv \qquad \textit{(eqn. 14)}$$

Adding these discrete sums together yields the total energy of the system. For 2→68 °Bx syrup this is 436,196 BTUs, 2→67 °Bx syrup this is 427,730 BTUs, and for 2→66 °Bx syrup this is 419,333 BTUs.

Evaporators and Thermal Efficiency

Quantifying the amount of energy needed to boil sap is the first step towards reducing emissions and lowering fuel costs. The second step is identifying the different types of evaporators, along with their corresponding fuels and efficiencies. The two most used types of evaporators are wood-fired arches and oil-fired evaporators. Wood-fired arches are designed to burn solid fuels (including coal, pellets, and wood chips) and to direct air movement from the firebox out through the flues and up the stack. The constant flow of heat from the firebox to the flue and the combustion of gasses along the length of the pan allows for consistent heating across the entire surface.[200] Efficiencies of wood fired evaporators range from 35-50% depending on insulation of the arch and pans as well as adequate air flow.[201] Beyond proper insulation techniques, one can improve heat transfer through forced draft. The forced draft blower increases the amount of oxygen supplied to the fire box, pressure builds and leads to an increase in both heat transfer and turbulence.[202] The increase in turbulence is due to a jet of air moving at a higher velocity than the surrounding air of the fire box, along with sharp edged grates to agitate airflow. Increasing turbulence reduces the insulation effect of the fluid boundary layer along the surface of the pans, increasing heat transfer to the metal. One can expect an increase in energy transfer of about 10-20% with the use of forced draft.[203]

Oil fired evaporators are more efficient than their wood fired counterparts with an efficiency of 73-80%, with newer models being closer to 80%.[203,204] They work by atomizing liquid fuels and creating radiant heat below the pans for efficient heat transfer.[200] Enhancements in efficiency have been researched through the addition of steam hoods and preheaters, which are more commonly associated with oil fired evaporators, but can be used with any arch if they are sized properly. Preheaters work like a condensing boiler, capturing the energy of the water vapor that is evaporated off the syrup and condensing it instead of losing it to the environment.[204] This energy is used to heat up incoming cold sap, greatly reducing the amount of energy needed to bring it to a boil. This process is performed with the help of a hood over the pan to lock in water vapor. Some units also use dry air to agitate sap and release water under the temperature of boiling, increasing the sugar concentration without expending extra heat.[203] The use of a preheater can increase efficiency by 15-20%.[203–205] Full steam enhanced units (Steam-Away™ produced by Leader Evaporator) have been rated by the manufacturer to increase evaporator rates by 65-75%.[124] Thermodynamically, we expect about a 16% decrease in overall energy consumption when sap is heated to just below the boiling point using ambient steam (see Figure 1).

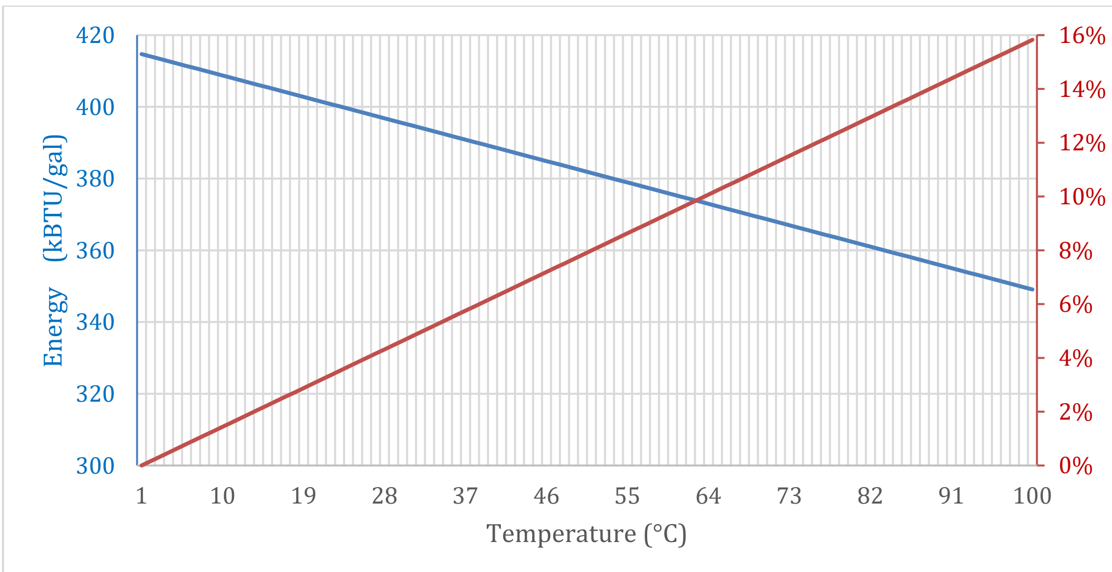


Figure 9 Remaining energy to make one gallon of finished syrup at 67 °Bx at different initial temperatures. The right axis represents the efficiency increase in terms of the total energy saved per gallon of finished syrup.

Additionally, flue pans with increased surface area can allow for enhanced heat transfer, raising the efficiency of any type of evaporator. Less common evaporator types would include those that burn natural gas and propane, or fully electric models. Natural gas and propane evaporators work similarly to the oil and wood fired arches mentioned above, but not much research has been done on their efficiency.[206] Because a propane or natural gas unit relies on the combustion of gas and the flow of air, it is expected to have a similar efficiency to that of a forced draft wood evaporator at around 65%-70%, consistent with studies of older gas based evaporators.[204,205,207] Electric units work by preheating sap and using a steam generator to create heat. The steam increases the pressure and temperature of the sap, and energy from condensate is captured and reused.[120] It is assumed that electric evaporators have an efficiency upwards of 90% and are most likely close to 100% as the units obey the same physical principles as electric resistance heating.[208]

Concentration

Another way to reduce fuel consumption is through the concentration of sap to a higher °Bx through reverse osmosis (RO) before boiling.[21,209] RO works by creating a pressure gradient either through a pump or a vacuum and running fluid through a micro or nano-filter membrane.[210] Normally, RO is used for the desalination or purification of water, where the permeate is the product and the concentrate is the waste. For producing higher concentrations of sugar, the concentrate is the desired product, and the permeate is the waste.

The energy necessary to produce finished syrup decreases hyperbolically as the input sugar concentration increases. Figure 2 is a direct illustration of the efficiency increases in boiling with concentration, meaning it does not factor in RO performance, energy, or the heat the RO unit applies to the sap. It should be noted that there is a loss of RO efficiency with colder input sap (75% at 40 °F), and the slight pre heating effect you get by running sap through the membrane (40 °F to 55 °F).[211] The act of bringing sap from just 2 °Bx to 4 °Bx results in fuel savings of 54.5%, while bringing sap to a high input concentration of 20 °Bx results in fuel savings of 94% (see Figure 2).

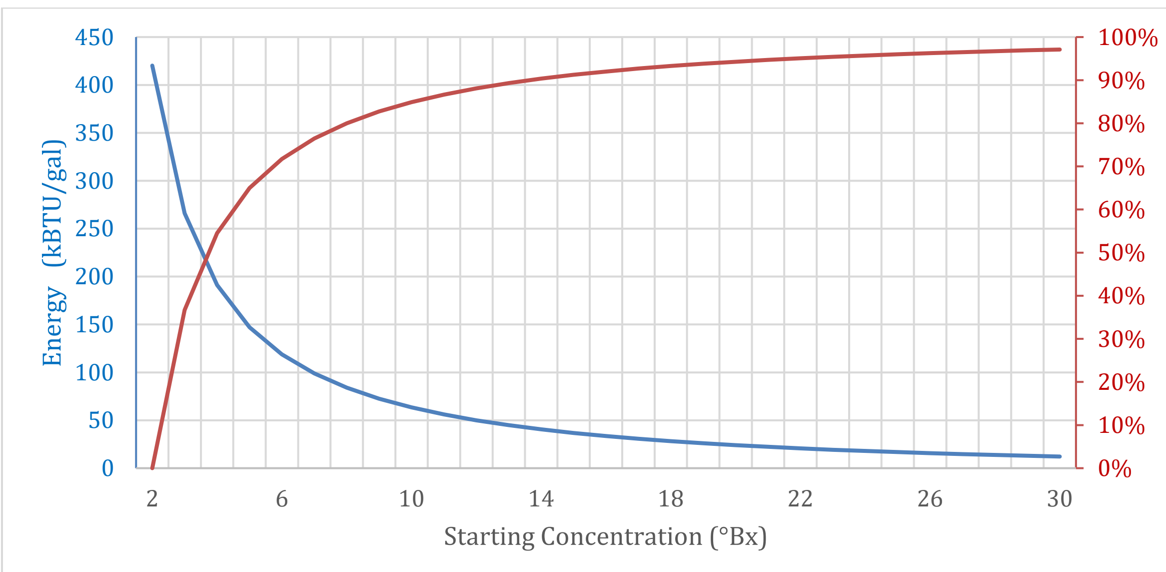


Figure 10 Remaining energy to boil sap into finished syrup (67 °Bx) and efficiency changes based on different starting concentrations.

While reverse osmosis has been rumored to change the flavor profile of syrup, research has shown that there is no significant change in the composition or flavor of syrup concentrated up to at least 21.5 °Bx.[19] The other major deterrent is the high upfront capital cost of an RO unit. However, as fossil fuels (like No. 2 fuel oil) continue to become more expensive, the payback period for an RO unit continues to decrease.

The question then arises: how does evaporator efficiency play into emissions reduction compared with changing the input concentration? Due to the hyperbolic decay of energy demand shown in Figure 2, we can see that as input concentrations get higher, their relative reduction becomes less. For example, you are only decreasing the necessary energy by 0.5% when you go from 19 to 20 °Bx input sap. So, as you get to higher input concentrations, it may be more cost effective to make your evaporator more efficient, as sizing up your RO unit will cost more for a given marginal energy reduction.

Utilizing the Model

Sugarmakers can use this model before the season to calculate how much energy and fuel they may need based on how much sap they expect to collect, what the average °Bx will be, whether they will concentrate the sap with RO, what °Bx they are bringing it to, and how efficient their evaporator is. Using only starting and ending °Bx, one can see how much sap they will need per gallon of syrup, and can calculate the boiling point temperature, change in enthalpy, change in mass, and change in specific heat for the solution on a °Bx by °Bx stepwise basis. Summing the energy needed to bring to a boil and change phases from starting °Bx to ending °Bx gives you the total energy for making a single gallon of syrup. One can then divide how much sap is collected over the course of the year and divide it by how much sap is needed to make one gallon of syrup to get the total amount of syrup produced over the course of a year. Multiplying this number by the energy calculated for one gallon gives you the total energy for the season. Knowing the efficiency of the evaporator, one can calculate what the actual energy use will be based on these non-ideal conditions. Knowing how much energy you need, one can divide this by the heat content of the evaporator fuel to calculate the expected quantity of fuel, and subsequent cost.

Conclusion

While current rules-of-thumb are sufficient for rough estimates of energy consumption in the boiling process using traditional methods, more exact calculation methods can provide better guidance for producer decision-making. As technology has advanced and RO concentration becomes more popular, sugarmakers can use this thermodynamic model to correctly size reverse osmosis units for their operations based on cost and energy. Additionally, by using the modified Jones Rule described above, producers can make more exact calculations with a wide range of concentrated sap inputs and variable °Bx outputs. In the long run, using these more exact methods of calculation for the most cost-intensive stage in the syrup making process can save significant amounts of money for producers.

Appendix C: Simple Vacuum-Tubing Fluid Model

Introduction

To produce maple syrup, one must first collect the sap from the tree. Traditionally, maple trees were tapped with spiles that had a bucket attached to capture the sap as it flowed out. However, research and advances in technology have given rise to a more efficient method of sap extraction: vacuum-tubing systems. This technique of sap extraction leverages the physics that allows for sap flow in the first place, creating larger yields from the tree throughout the season. Sap exudation is caused by the freeze thaw cycle that takes place in the early spring season. The xylem from a maple tree contains sap (a byproduct of photosynthesis) and gas bubbles, and acts as a pipeline for transporting water throughout the tree.[212] When temperatures drop below freezing, there is a negative pressure in the tree relative to the atmosphere, which draws water in from the roots.[213] When a thaw occurs, there is a positive pressure in the tree and the gas expands in the xylem. This expansion coupled with an osmotic sugar concentration gradient causes sap to flow out from the fibers.[214] When one taps into the xylem, there is a larger wound for the sap to flow out of, and more sap can escape from the tree. By attaching a tubing system to the tap, and removing air, one can increase this pressure gradient between the tree and the tap hole, which both increases the range of temperatures sap will flow, and the flow rate of sap during those runs.[215]

The following model was created to estimate a conservative yet realistic vacuum tubing model for sugarmakers of varying sizes, for the purpose of assessing the energy and emissions impacts of the entire production process. The methods are adapted from The New York State Maple Tubing and Vacuum Notebook (NYS Notebook) out of the Cornell University Extension Cooperative.[216] Their methods were altered to create a tubing model for different producer archetypes (characterizations of the industry based on production scale), meaning they are modeled without sugarbush data. Below is a breakdown of the assumptions made when modeling these archetypes, and the physical principles that underlie them. While producers may be able to use this as a tool to optimize a tubing network, this model is primarily used to estimate the amount and diameter of tubing used at different production scales.

Methods

To set up a general model of a vacuum-tubing system, some assumptions need to be made about the physical characteristics of the sugarbush (e.g., slope, spatial density of tappable trees, and acreage). Initial decisions were made with the guidance of the NYS Notebook, which were then modified to reflect a system with a single collection point and multiple independent lines. In the guide, all parameters are established in terms of acres (two-dimensional), however all branches of tubing are linear (one-dimensional) and independent of one another (individual lines stemming from the lone collection point). In practice, the NYS Notebook method estimates the number of trees a mainline serves per acre as an average, which holds independently for each acre. However, trying to visualize the scaling of a network of linear objects (tubing) in two-dimensional space lends itself to configurations that could use more tubing than one would reasonably expect. Figure 1 illustrates this issue, as each plot is scaled as one acre. As you try to access the area at the top end of the one-acre plot in Figure 1, a new line must run that length each time. This redundancy leads to more lines, each of which serve fewer trees when the sugarbush is longer than it is wide ($l_{m2} < l_{m1}$). The most realistic model of a network of independent lines is to have each mainline serve as many trees as possible, rather than many repetitive (parallel) branches.

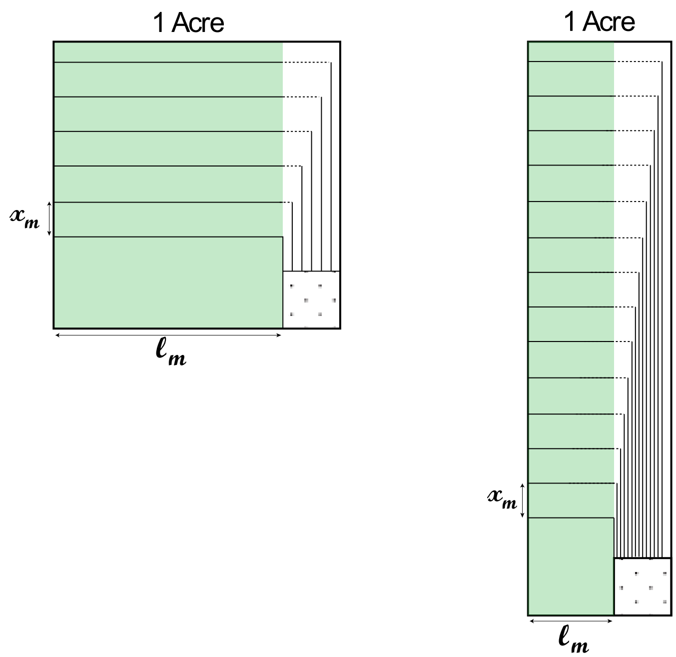


Figure 11 Scaling problem for mainline tubing in variable spatial plots. x_m represents the distance between mainlines, which is constant between the two plots (as it is based on the density of tappable trees). l_{m1} and l_{m2} represent the length of mainline serving the trees within the sugarbush. The dotted horizontal lines are assumed to be zero as all lines would run parallel and close together in this configuration.

The distance between mainlines (x_m) is constant between the two plots because it is based on the density of tappable trees in the sugarbush (see equation 5). Comparing the two plots in Figure 1, we can calculate the total amount of tubing by using eqn. 1:

$$N * (l_m) + \sum_{i=1}^{N} i * (x_m) \qquad (eqn.\ 1)$$

Notice that the discrete sum in eqn. 1 highlights the redundancy of tubing when the sugarbush is not a square, causing the right side of Figure 1 to use more than two times the amount of tubing per tap. In order to balance the length of mainline tubing with the number of lines, the sugarbush is approximated as a square.

Now that we have made this assumption, we can calculate the amount of mainline tubing per acre. A modified version[2] of how the NYS Notebook arrives at the mainline tubing per acre is by taking the square footage of an acre, dividing it by the assumed number of tappable trees per acre (100-120 being a good estimate), and taking the square root of this fraction to get the total linear distance of tappable trees in a one-acre area (eqn. 2):[217]

$$\frac{ft.\ mainline\ tubing}{acre} = \sqrt{\frac{\frac{sqft}{acre}}{\frac{tappable\ trees}{acre}}} \qquad (eqn. 2)$$

In theory, multiplying this number by the total acreage gives you the total length of tubing. However, as we have highlighted in Figure 1, density is an intensive quantity, meaning it does not scale with the size of the operation; doubling the acreage does not double the density of tappable trees but rather just the total number of tappable trees. So, as the operation gets bigger than one acre, the total amount of mainline tubing would increase, but the number of trees each mainline serves would remain the same (as would the diameter necessary to accommodate the volumetric flow of sap in each mainline), which is unrealistic. Going back to our approximation of the sugarbush as a square, this means that as we scale up the operation, it must increase equally in both dimensions to maintain shape. You would need to increase the diameter of these mainlines because the total volume of sap that they are moving is larger, and the length of each mainline would be longer (resulting in more frictional head loss).[218,219]

A more practical model assumes that you connect more trees to a mainline on the way to the fixed collection point, meaning you have fewer mainlines, with each serving more trees (see Figure 2).

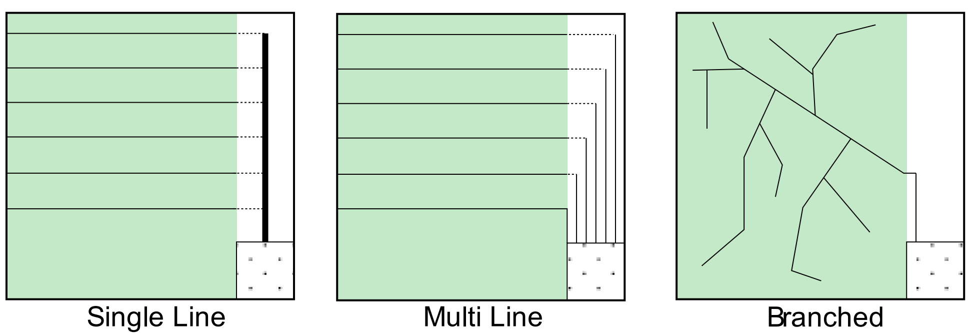


Figure 12 Different plausible configurations of a tubing system from most ordered (single-line) to most variable (branched). Figure derived from Figure 3.2 in NYS Notebook.[220]

The left-hand of Figure 2 illustrates this concept, where a large mainline acts as a highway, with each smaller mainline acting as an artery to that highway, and the laterals (not pictured) as capillaries. While this approach limits the amount of tubing, most sugarbushes are not as symmetrical as we have approximated, making a branched configuration more likely when

[2] The NYS Notebook leverages that one knows the length of the mainline and is trying to figure out tappable trees per acre.

sugarbush topography and shape are variable. To approximate the extra tubing needed for a branched layout, multi-line collection for a square shaped plot gives a conservative estimate while employing the symmetry we have used up to this point. To scale a multi-line system with the acreage growing in a square shape, we can apply the correction to eqn. 2 shown in eqn. 3:

$$\frac{mainline\ tubing}{width} = \sqrt{\frac{\frac{sqft}{acre}}{\frac{tappable\ trees}{acre}} \times \frac{total\ acreage}{total\ acreage}} \qquad (eqn. 3)$$

The result leverages the intensive property of the density of tappable trees, meaning the denominator will not change, but the total square footage will. Notice that the units of the results now change to being in units of tubing per width, as the square root of the square feet of total acreage equals the length and width of our square sugarbush. We now know how much tubing there is across the width (x-direction) of the sugarbush and can calculate the number of mainlines as a function of the distance between tappable trees in the lengthwise direction (y-direction) as well.

Using the information above we can also make decisions about the lateral lines. Research from UVM and Cornell Extension have found that 5/16" lateral tubing yields the best results overall, as it limits bacterial growth more than a 7/16" lateral and allows more flow than a 3/16".[217,221] Additionally, research has shown that six taps per lateral leads to the highest productivity per tap. The average length of a six-tap lateral can be calculated by first figuring out the number of laterals per mainline and the average distance between mainlines. To calculate the number of laterals per mainline, you can round down the product of the number of tappable trees per acre and the square root of the number of acres (eqn. 4). This will give you the number of taps along a given length, with that length being for the mainline.

$$\frac{tappable\ trees}{length} = rounddown\left(\frac{tappable\ trees}{acre} \times \sqrt{no. of\ acres}\right) \qquad (eqn. 4)$$

Now that we know how many taps there are per main line and taking the conservative estimate of one tap per tappable tree,[3] one can calculate how many laterals per mainline by dividing this number by six taps per lateral. Knowing how many taps per acre and the number of acres also gives us the total estimated number of taps, so we can calculate how many mainlines one would need to fulfill this. Because the number of laterals, taps, and mainlines are whole numbers, the rounding will lead to slightly fewer taps than initially calculated as a function of tap density. This provides a slightly more realistic result, as it is unlikely that there would be a uniform tappable tree density across the whole sugarbush. Knowing the length of one side of a square sugarbush is the square root of the number of total acres and dividing this number by the number of mainlines

[3] Exudation productivity may decrease per tap when more taps are added to a tree, making calculations regarding production harder to quantify.

leads us to the average distance between mainlines (eqn. 5). This number can be used to calculate the average length of a lateral line.

$$Avg. Lateral\ Length = \sqrt{\frac{sugarbush\ width \times avg\ distance\ between\ main\ lines}{\frac{laterals}{main\ line} \times \frac{taps}{lateral}}} \times \left(\frac{taps}{lateral} - 0.5\right) \qquad (eqn. 5)$$

The reason there is an extra 0.5 subtracted from the number of taps per lateral is that if a mainline is to run through any given area, it will split the distance between two tappable trees.[217] Thus, the distance from the mainline to the first tree averages half the distance between tappable trees. Now we have an intuition of the number of mainlines, the number of lateral lines, the density of tappable trees, the size of the sugarbush, the number of taps, the diameter of the lateral lines, and the average distance between mainline tubing. Next, we will focus on sizing mainline tubing to accommodate vacuum and estimating the resulting increase in yield.

Sizing Vacuum

Knowing the physical characteristics of the sugarbush allows for the proper sizing of tubing and vacuum to reduce losses along the lines. In a single wet line system, maple sap comes out of the tubing in a configuration that is approximated by open channel flow, meaning the pump is rarefying a layer of air above the sap, creating a vacuum.[222] Below the layer of air is liquid sap, which is flowing based on gravity and the pressure differential between the tree and the outflow. The most rigorous modeling of a complex tubing system such as this would include analytical solutions to the Navier-Stokes equations using computational fluid dynamics.[223] However, the goal of this model is to estimate the vacuum pump and tubing sizes necessary to facilitate laminar, stratified flow in the system. Starting with our anticipated outcome (we are trying to attain a specific pressure at the tap), some assumptions can be made about the flow to calculate a system that would facilitate such solutions. The main characteristics the system should have include:

1. The ability to handle average flow, which can be approximated as steady for the purposes of design.
2. The shape of the tubing limits flow in the radial and azimuthal directions
3. The flow is fully developed and can be approximated as a fluid moving between a stationary plate and a non-stationary plate moving in the direction of flow.
4. The no slip condition is obeyed at the bottom of each fluid layer.
5. Shear stress is equal at the boundary of the liquid and the gas.

From these outcomes, three of the four conditions needed to simplify the Navier-Stokes equations into the Hagen-Poiseuille equations are met.[224] The last condition is that the flow be axisymmetric. Because we simplified the cross section of the flow as being between two parallel plates, we can extend this assumption into three dimensions, where the shear along the boundary obeys the no slip condition for the liquid in contact with the gas and the tubing. This configuration would allow for two-dimensional shear (albeit at different strengths) in cylindrical coordinates, leading to a developed flow that can be approximated as axisymmetric. A simplified system can then be constructed using Hagen-Poiseuille to estimate flow rates based on pressure (eqn. 6):

$$Q_{sap} = \frac{\Delta P_{tree-tubing} \Pi R_{tap\ hole}^{4}}{8\mu_{sap} L_{tap\ hole}} \quad (eqn. 6)$$

(where Q_{sap} is the flow rate of sap, $R_{tap\ hole}$ is the radius of the tap hole, $L_{tap\ hole}$ is the depth of the tap hole, μ_{sap} is the dynamic viscosity of sap,[225] and $\Delta P_{tree-tubing}$ is the pressure gradient between the tree and the tubing system). The length of the tap hole was assumed to be 2 inches. The only unknown in this equation is the internal pressure of the tree, which varies by hour, day, season, and year depending on the ambient conditions. Based on experimental results of productivity increases from the addition of a vacuum, the highlighted band in Figure 3 represents the most likely average tree internal pressure throughout the day. Because flow rate is proportional to tree internal pressure, average pressure gives the average flow of sap through the system.

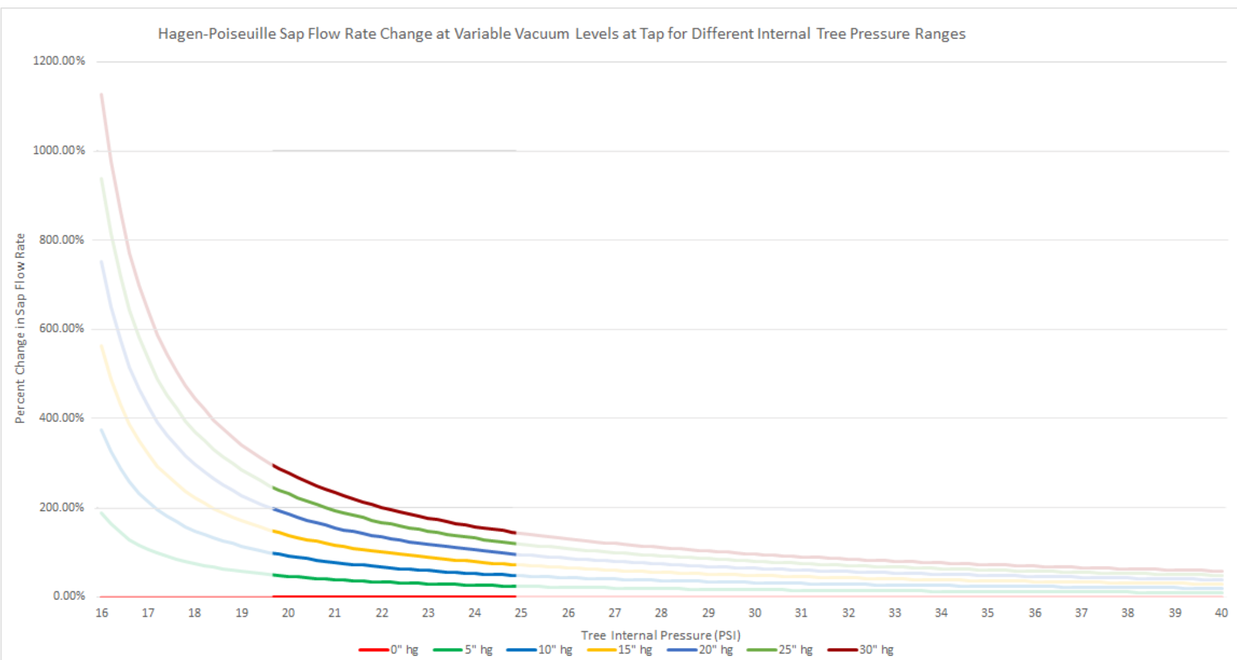


Figure 13 Changes in sap flow based on pressure differential between the tree and tap hole at different vacuum levels. Changes are measured as a percentage with respect to flow at atmospheric conditions. Vacuum is measured on inches hg removed from the tubing (making 0 "hg atmospheric conditions).

The question then becomes: why not max out on vacuum to yield the highest results? As per the guidance of the NYS Notebook, the economics of vacuum pump sizing plays a role in this decision. The marginal benefit you might get from producing more syrup may be offset by the energy costs of running the pump, as well as the upfront capital investment in a larger pump. A best practice rule of thumb is to size the pump to achieve 15" Hg vacuum at the tap. While many pumps are rated for 29-29.9" Hg, losses along the line from both friction and leakage (1.5 cfm per lead to a reduction in vacuum at the most distal tap).[222] Determining these losses mathematically will help to determine the length for each mainline diameter for each size of operation.

We can again assume ideal system conditions to size the system. Setting 15" Hg (50% air removal) as the target pressure at the tap, we can select a pump that matches the size rating of the system. The Becker catalog[49] was used to select pumps within the range of taps at a given size. The rate of air removal was also factored to ensure that the capacity of the pump would be enough to hold vacuum over the lines including expected connector losses. For every 100 taps, one can expect 1-1.5 cfm of air leakage into the system.[222] For smaller sugarbushes, this number is closer to 1 and for larger sugarbushes, this number is closer to 1.5; (for medium sized sugarbushes, we chose 1.25 cfm leakage).[222] Taking leakage losses into account, we allocated the rest of the pump's capacity and evenly distributed it among the lines, representing the flow rate of air at the tap. Knowing the flow rate of air and the specifications of the lateral lines from the previous section, we can leverage this information to calculate line loss along the lateral. This pressure drop was used in the Hazen-Williams head loss equation[4] (eqn. 7) to determine what the change in pressure is across the mainline only:

$$\mathrm{H} = \frac{10.67 L Q^{1.85}}{C^{1.85} d^{4.87}} (eqn. 7)$$

Once the frictional losses [H] are known along the mainline (a function of length [L], flow rate [Q], material [C], and diameter [d]) we can iterate by allocating the total vacuum from the pump proportional to the cross-sectional area, as more air would be removed from larger tubing diameters. The derivation below shows the process of obtaining the pressure losses from each step in the tubing line.

Pressure Derivation:

By setting up the parameters of the sugarbush as square in dimension and uniform in slope, the critical path can be defined as the longest line from pump to tap (see Figure 4).

[4] Hazen-Williams head loss is an empirical formula. The SI version of the formula was used in calculations. For the coefficient of friction (C) for LDPE, the high-end estimate of 140 was used.[226]

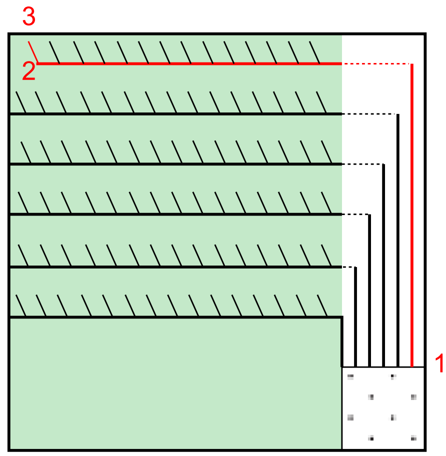


Figure 14 Map of critical path for a multi-line mainline configuration. X represents the collection point (1), (2) represents the mainline lateral junction, and (3) represents the tap hole at the most distal node from the collector. Note that the amount of mainline tubing vs. lateral line tubing is not to scale.

If the allowable drop in pressure is satisfied for the critical path, it is satisfied for all the other lines in an ideal system. The pressure loss along this path from the tap to the collector is calculated as:

$$\Delta P_{1\rightarrow 3} = \frac{8\mu_{air}L_{lateral}Q_{air,tap}}{\Pi R_{lateral}^{4}} + \frac{8\mu_{air}L_{mainline}Q_{air,junction}}{\Pi R_{mainline}^{4}} = P_{pump} - P_{tap} \qquad (eqn. 8)$$

(where P is the pressure, R is the radius, μ is the dynamic viscosity, Q is the flow rate, and L is the length). The only unknown in eqn. 8 is the radius of the mainline ($R_{mainline}$). The flow rate of air determined by the pump is split proportional to the cross-sectional area of the mainlines. However, the conditions of the system do not significantly alter density, as the associated expansion between the lateral line and the mainline is minor and no heat is flowing into or out of the system. Therefore, we can justify using the volumetric flow rate continuity equation over the mass flow rate (eqn. 9):

$$Q_{air,tap} = \frac{Q_{pump}}{\#\,main\ lines} - \left(\frac{Q_{leakage}}{junction} \times \frac{\#\,junctions}{main\ line}\right) \qquad (eqn. 9)$$

(where $Q_{air,\ tap}$ is the flow rate of air at the tap, Q_{pump} is the flow rate of air out of the tubing supplied by the pump, and $Q_{leakage}$ is the flow rate of air into the tubing). The number of junctions is the number of places a leakage could occur. We can further simplify the model of this system to approximate all laterals connecting at one junction, instead of at different points along the mainline. By modeling the system in this way, one junction incorporates the losses that would be incurred across all laterals of a given mainline. Even though there is a change in size (and a corresponding expansion minor loss) when the lateral connects to the mainline at an individual node, there needs to be enough space to accommodate all the air outflows for the system, making the continuity at an individual point a decent approximation for the physical behavior across the whole length of the mainline.

Eqn. 8 can also be expressed as the sum of the pressure drop from the pump to the junction of the lateral and mainline (1→2 in Figure 4), and the pressure drop from the junction to the tap (2→3 in Figure 4). Then, the lateral line from 2→3 can be rewritten as eqn. 10:

$$\Delta P_{2\to 3} = \Delta P_{1\to 3} - \Delta P_{1\to 2} \qquad (eqn. 10)$$

We already allocated the junctions of the lateral lines and their subsequent losses (leakage rate) to the mainline section of the system (1→2). This means that at point two in the diagram above, there should only be pressure losses attributable to friction. All the guiding assumptions for Hagen-Poiseuille also allow for the use of the Bernoulli equation[227] (eqn. 11):

$$\frac{P_3}{\gamma_{air}} + z_3 + \frac{\left(\frac{Q_{air,tap}}{A}\right)^2}{2g} = \frac{P_2}{\gamma_{air}} + z_2 + \frac{\left(\frac{Q_{air,junction}}{A}\right)^2}{2g} + \frac{10.67\, L\left(Q_{pump}\right)^{1.852}}{C_{LDPE}^{1.852}\, d_{lateral}^{4.8704}} \qquad (eqn. 11)$$

(where *P* is the pressure at a specific point denoted by the subscript, *z* is the elevation in units of distance, *g* is gravitational acceleration, and *γ* is the specific weight of the substance—density times gravitational acceleration). Attributing continuity between the flow rates, we can relate the change in slope, change in pressure, and the Hazen-Williams head loss formulation to determine the change in pressure across the lateral *(eqn. 6)*.

$$\Delta P_{2\to 3} = \frac{10.67\, L\left(Q_{air.tap}\right)^{1.852}\gamma_{air}}{C_{LDPE}^{1.852}\, d_{lateral}^{4.8704}} - \Delta z_{lateral}\, \gamma_{air} \qquad (eqn. 12)$$

This will allow us to accurately gauge losses across the mainline only, as we already know the specifications of the lateral line. Relating *(eqn. 8), (eqn. 10),* and *(eqn. 12),* we get:

$$\Delta P_{1\to 2} = P_{pump} - P_{tap} - \left(\frac{10.67L\, \left(Q_{tap}\right)^{1.852}\gamma_{air}}{C_{LDPE}^{1.852}\, d_{lateral}^{4.8704}} - \Delta z_{lateral}\, \gamma_{air}\right) = P_{pump} - P_{junction}$$
$$(eqn. 13)$$

Reapplying Bernoulli across this section of mainline from point 1 to point 2, we can see the relation in equation 13 equals:

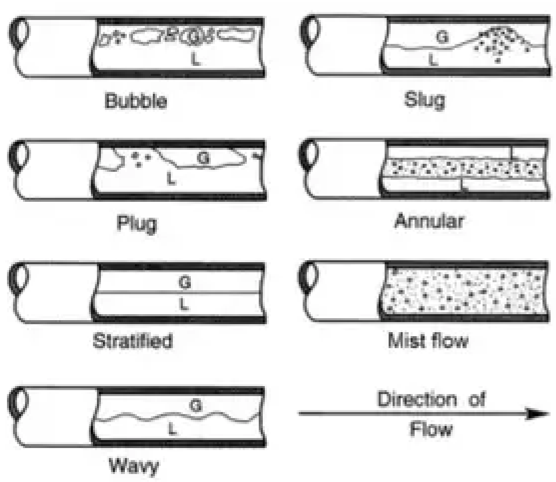
$$\Delta P_{1\to 2} = \frac{10.67\, L\left(Q_{pump}\right)^{1.852}\gamma_{air}}{C_{LDPE}^{1.852}\, d_{main\ line}^{4.8704}} - \Delta z_{main\ line}\, \gamma_{air} \qquad (eqn. 14)$$

Note that the flow rate has changed from *(eqn. 12)* and is now Q_{pump}, so as not to double count the leakage from the laterals. Additionally, the change in height between the ends of the mainline is also reflected in *(eqn. 14)* as well as the new diameter, $d_{mainline}$. Choosing a starting value for the mainline equal to that of the lateral, one can now iterate like the Hardy-Cross method, to arrive at the correct diameter for each individual mainline. Because the vacuum flow rate is proportional to the cross-sectional area of air passing through the pipe for each mainline, the larger mainline diameters will command a larger share of the total volumetric flow.[217] Once the difference between iterative terms has converged at a critically small difference (<0.02%), the cross-sectional area allocated for air in each pipe has been optimized for the simple system and the best tubing diameter is now known.

Two Phase Flow

Now, the cross-sectional area for sap needs to be considered to correctly size the tubing for holding vacuum pressure.[222] The ratio of gas velocities to liquid velocities can determine the type of flow regime that sap will behave as within the tubing. We can best approximate this as a 2-phase flow (See Figure 5).[228]

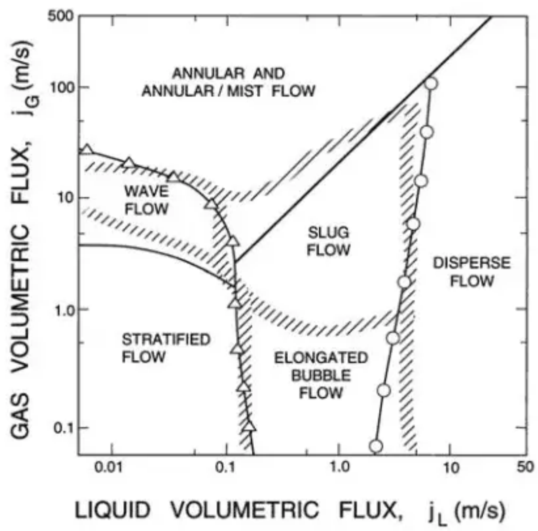
Figure 15 Sketches of flow regimes for two-phase flow in a horizontal pipe. Source: Weisman, J. Two-phase flow patterns. Chapter 15 in Handbook of Fluids in Motion, Cheremisinoff N.P., Gupta R. 1983, Ann Arbor Science Publishers. Source Credit[228]



As a gas moves over a liquid, its speed dictates the surface effects of the sap flow.[229] If there are large enough ripples along the surface, creating slug or dispersed bubble flow, there will be a blockage in the gas flow stream and reduce the effectiveness of the vacuum. Thus, the proper sizing of the sap area will help allow for the stratified or wavy flow necessary to optimize the vacuum set up. Again, the assumption that the cross-sectional area of sap, and therefore air, will remain constant will serve as a decent approximation in estimating the flow, as the hope is that perfectly stratified flow will occur in the ideal case. Remember that this is a simplified version of a tubing system at ambient conditions, so line maintenance issues, sharp bends in the tubing, and changes in the homeostasis of the system would alter these cross-sectional areas and cause more turbulent flow of both air and sap than the laminar assumption.

The length and radius of the tap hole are determined by the tapping guidelines set out by research at Cornell University, stating that 5/16" tap diameters and 2" bore length should be used for best practice. Here we can use the same approximation that all the laterals join at a single point and that the flow does not deform to determine the area. Using an engineering flow regime chart, we can determine the sap cross-sectional area that satisfies the range of proportions which fall within the stratified and wave flow regimes (see Figure 6).

Figure 16 A flow regime map for the flow of an air/water mixture in a horizontal, 2.5cm diameter pipe at 25◦C and 1bar. Solid lines and points are experimental observations of the transition conditions while the hatched zones represent theoretical predictions. Source: Mandhane, J.M., Gregory, G.A. and Aziz, K.A. (1974). A flow pattern map for gas-liquid flow in horizontal pipes. Int. J. Multiphase Flow Source Credit[228]



Taking the pump flow rate and dividing it by the air flow cross-sectional area found above, we can get the gas volumetric flux. Similarly, taking the flow rate out of the tree from *(eqn. 9),* and multiplying it by the number of laterals, we can find the max flow rate (all the sap from all the taps along the single mainline).

$$Q_{sap} = \frac{\Delta P_{tree-tubing} \Pi R^4_{tap\ hole}}{8\mu_{sap} L_{lateral}} \quad (eqn.15)$$

Note that we are using $L_{lateral}$ instead L_{tap} like in equation 6. This choice was a result of the simplification of all the leakage coming from a single point at the end of the mainline junction. Because we assumed that only Bernoulli applied along this line, the effective length of the tap hole is the length of the lateral serving it.

Using the range of liquid fluxes allowed, we can solve for the liquid cross-sectional area. By adding the air and sap cross-sectional areas, we can now find the area of each section of mainline tubing in the system. The last step is to account for the fact that the system is not ideal. The nominal pipe size found in the ideal system calculations can be sized up to best approximate variable system conditions that would have to be met (including peak flow), as the calculations above are for ideal average flow. Note that utilizing the change in pressure across the tubing rather than from inside the tree to the tubing results in more practical sizing for a maple syrup operation, rather than using the instantaneous peak flow (which would oversize the tubing).

Conclusion

The modeling effort above is a simplified version of reality and can be used as an auxiliary model to help benchmark system productivity, and total material used in the sugarbush on average. The main assumptions can be broken into three parts: sugarbush characteristics, system configuration, and fluid mechanics. The assumptions made about the sugarbush were used to simplify symmetry and uniformity for setting up a tubing system. Once the characteristics of the sugarbush were determined, the system was assumed to consist of mainlines connected to a central receiver (the pump). The configuration of the system led to simplifications regarding head loss, with uniform leakages, no significant bends, and minor losses from fittings or taps. Once this simplification was made, the flow could be best approximated by Hagen-Poiseuille and Bernoulli as the system was modeled as two disjoint pieces (sap and air) with different flow rates. For a more rigorous solution, one could solve the Navier-Stokes equations for all the pipes and use the Hardy-Cross method to calculate flow rate. However, for the purposes of assessing the sustainability of a tubing system or its performance, this simple model allows for realistic yet conservative assumptions of vacuum size, tubing diameter, and tubing length.

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