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Estimating Economic and Environmental Impacts of Red-Wine-Making Processes in the USA

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Abstract: The goal of this study was to examine cost impacts using techno-economic analysis (TEA) and environmental impacts using life-cycle assessment (LCA) for the production of red wine. Three production scales, denoted as "small" (5000 gal per year), "medium" (50,000 gal per year), and "large" (500,000 gal per year) were chosen for analysis. For example, the consumption of water, energy, greenhouse gas emissions, and solid waste generation were considered in order to estimate environmental impacts. A spreadsheet-based economic model was also developed. The results of the LCA and TEA were compared amongst all production scales. The results of the LCA showed that both bottle manufacturing and various wine-making processes contributed the greatest environmental impacts. For TEA, the relationships between costs and profits increased as production scale increased; exponential trend lines could describe the data, but linear models were better. This information can be useful when considering what size of winery might be appropriate to invest in, or what operational categories may be most impactful in terms of costs and environmental burdens and, thus, may be targets for efficiency improvements.

Keywords: sustainability; environmental impacts; costs; grapes; wine; bottling; vineyards

1. Introduction

Throughout history, wine was, and continues to be, one of the most important, influential, and popular alcoholic beverages in the world. In 2005, the consumption of wine accounted for 8.6% of the total alcoholic beverage consumption throughout the world, preceded only by spirits and beer [1] Wine is made from fermented grapes or other fermented fruits. Grapes can ferment without the addition of acids, sugars, enzymes, water, or other nutrients because of their natural chemistry, as well as natural yeast inoculation [2]. Under the action of yeast, the sugars in the grapes are converted into alcohols (primarily ethanol) and carbon dioxide, thereby making wine. In addition to its role as a popular beverage due to its distinctive flavor and aroma, wine can also act as a psychoactive drug, as wines are alcoholic beverages and thus can have intoxicating effects.

The history of wine is intimately connected to the history of humanity. The earliest traces discovered so far occurred in 6000 before Christ (BC) in Georgia and 5000 BC in Iran [3,4]. The first recovered crushed grapes were dated to 4500 BC and were discovered in Macedonia [5]. The first winery was dated to 4100 BC, and was discovered in Armenia [6]. Wine was an occurring theme throughout the Bible.

Overall, wine making begins with proper selection and cultivation of appropriate grapes and ends with bottling of the finished wine. In terms of final products, wine making can be divided into still wine production, which produces wine without carbonation, and sparkling wine production, which produces wine with carbonation (the most famous of which is champagne, which only originates from the Champagne region in France). Still wine production can be further subdivided into red wine, white wine, rose wine, sweet wine, and other specialty wines [7]. To produce the various wine products, similar yet unique processes are typically used. For example, for red-wine production, red grapes are harvested, de-stemmed, and crushed; all berry parts including skins, pulps, and seeds are fermented. Sometimes there may be double fermentation for red wine: first to convert sugar into alcohol using yeast, and then to convert malic acid into lactic acid (known as malolactic fermentation). Secondary fermentation accomplishes several key aspects, including adding flavors, reducing acidity, and ensuring stability in the bottle [7].

According to [8], red wine making is an extractive process involving the skins and seeds. They found that because of high levels of antioxidants (e.g., tannins and anthocyanins) that were extracted during the production process, red wine was less susceptible to oxidation. Secondary fermentation in red and even some white wines is also beneficial for stability against spoilage and in-bottle fermentation, because malic acid was consumed by conversion to lactic acid via *Lactobacillus oeni* [7].

White wine, on the other hand, is only fermented by yeast and then chilled and stabilized (thus, the wine-making process is considerably simpler than that for red wine). Only the juice or "must", which is pressed from the pulps of white grapes, is fermented. Thorough filtration must be used in order to remove all contaminants and microorganisms and, thus, prevent malic acid fermentation after bottling. The whole process is quite quick and, therefore, can produce wines with dry, crisp, and aromatic palates vis-à-vis red-wine profiles. Compared to red-wine production, white-wine production needs much greater control of oxygen, hygiene, yeast nutrition, and temperature. Thus, it is possible to produce an acceptable red wine in just "backyard" conditions, but it can be more difficult to make a high-quality white wine in the same environment [7]. For example, white wine can be prone to oxidation; thus, sterile filtration must be used for proper stabilization. Chilling before bottling is required in order to precipitate excess potassium bi-tartrate salts, to reduce the formation of crystalline deposits during refrigeration. Additionally, clay can be used to remove proteins in the wine that can coagulate to form haze; this is especially true during storage and transportation, especially if the wine becomes warm. Copper sulfate is often used to remove hydrogen sulfide, which can be formed during yeast metabolism of proteins, which can occur during late fermentation [7].

In contemporary society, consumers are demanding more environmentally friendly products. This includes food and drinks, such as wine. Companies are becoming more attuned to these demands, and are changing production processes, as well as entire supply chains, to achieve these ends. Some are even pursuing third-party sustainability certification, such as that offered through BCorporation (https://bcorporation.net). Of course, implementing sustainability initiatives must make economic sense. Toward that end, life-cycle assessment and techno-economic analysis are two ways of quantifying and understanding business operations.

Life-cycle assessment (LCA) is the accounting of all environmental burdens associated with a product, a service, or a process, from raw material to waste/end-of-life [9]. It was originally developed in the United States of America (USA) at the Midwest Research Institute around 1970 [10], and the LCA approach as it is currently used was defined by ISO, including goal and scope definition, inventory analysis, impact assessment, and interpretation [11]. To date, there are only a few published studies of LCA in wine-making processes and winery operations. For example, [12] conducted a "cradle-to-grave" LCA (total LCA) to identify and assess the environmental burdens throughout the life cycle of a bottle of white wine, including grape planting, wine production, wine bottling, packaging, distribution, and disposal of the wine bottle. In their research, glass bottle production was found to be the most impactful to the environmental performance of the white-wine supply chain. In their analysis of agricultural production, including vine planting and grape production, vine planting was not negligible to environmental impact compared to the whole agricultural operation. [13,14] also carried out "cradle-to-grave" analyses that included distribution. These authors also found that the production of wine bottles plays a very important part in the environmental effects of the life cycle of wine. Other studies also considered vine planting [15,16], from which the vine planting contributed considerably to environmental impacts. Several other studies only conducted "cradle-to-gate" (i.e., the system boundary ended at the farm gate) research [15,17]. They did not account for distribution in their studies. However, from their conclusions, glass-bottle production was still the most significant element that affected the environment. Even so, there is a dearth of literature that examined life-cycle assessment of vineyards and wineries.

Techno-economic analysis (TEA) is widely used in the food, bioprocessing, and chemical engineering industries. The usefulness of TEA for cost analysis, potential profit assessment, and production strategy determination was extensively demonstrated. For example, [18] developed a cost model that utilized existing food factory data, and analyzed them systematically to understand various characteristics of unit operations in the food industry. Another TEA was used to characterize and improve dairy goat systems in Andalusia [19], where a profitable production strategy was determined. In terms of wineries and wine making, however, only a few studies were published. [20] developed an economic decision-making model for small to medium-sized wineries, and they found break-even prices ranging from $3.50 to $6.00/750-mL bottle for winery sizes between 5000 gal per year and 100,000 gal per year; the larger the winery size is, the lower the break-even price becomes. Furthermore, an economic cost model was developed to evaluate costs of raw materials such as grapes, labels, and bottles [21]. They found that the cost of the raw materials had a substantial effect on the annual net profit; in this study, winery profits could fluctuate more than 60% when the grape price alone changed by 25%. Furthermore, [22] compared different approaches to calculating profitability and productivity measures using a non-parametric technique. They found that none of the methodologies tested were significantly better than the others based on their evaluations of winery economic performance. Even though a few economic analyses were applied to wine making and winery operations, to the authors' knowledge, there is no complete TEA for wine-making processes that was published.

Because of the paucity in the literature related to benchmarking vineyards and wineries, this study was carried out to examine environmental and cost impacts for red-wine production processes in the USA. The LCA encompassed vine planting to product distribution, while the TEA also considered this supply chain, but was conducted for small (5000 gal per year), medium (50,000 gal per year), and large (500,000 gal per year) wine production. It is our hope that this study can help move the industry forward toward greater sustainability by providing baseline information.

2. Materials and Methods

2.1. Life-Cycle Assessment (LCA)

The system boundary that we used for life-cycle assessment and techno-economic analysis encompassed vine planting to wine-bottle disposal. This included vine planting, wine making, distribution, and bottle disposal. Energy and water consumption within this system were input impacts, while greenhouse gas emissions and solid waste disposal were output impacts (Figure 1). Units for LCA inputs and outputs included energy consumption in kilojoule (kJ), water consumption in gallon (gal), greenhouse gas emissions in grams of carbon dioxide equivalent (g $CO_{2eq.}$), and solid waste disposal in grams (g).

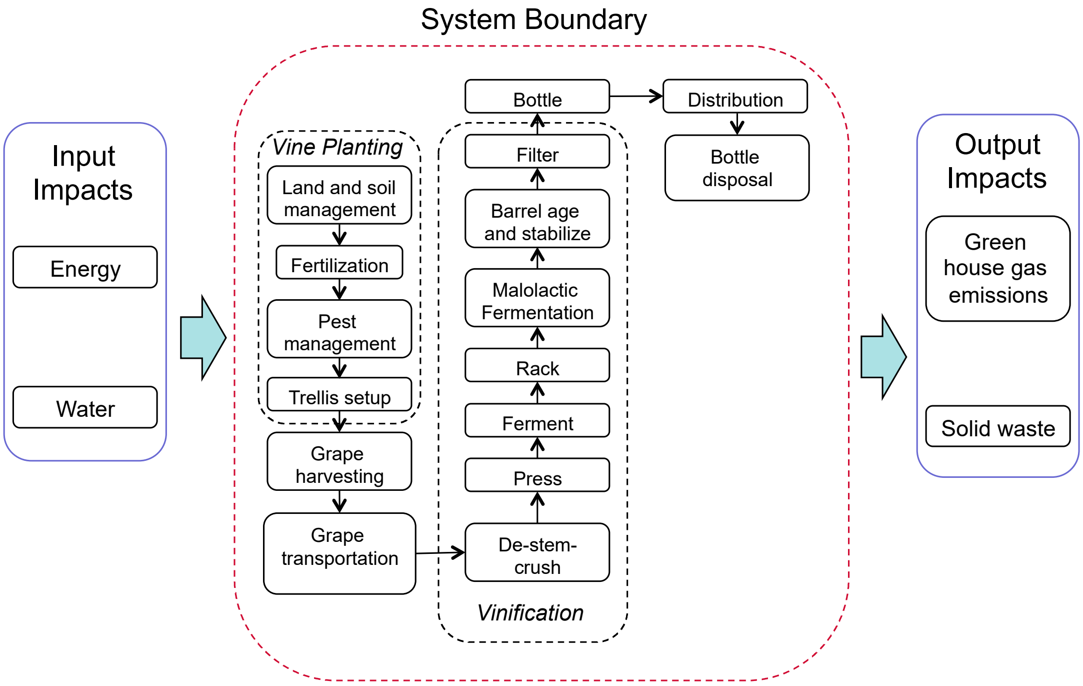

Figure 1. System boundary, inputs, and outputs used for life-cycle assessment (LCA) and techno-economic analysis (TEA) in this study.

We assumed that 70% of glass was recycled for wine-bottle production. The chosen functional unit (FU) for this study was a 750 mL bottle of wine.

Data regarding energy consumption and greenhouse gas emissions for each stage of wine making were assessed via EioLCA [23] (Tables 1 and 2), using the 2002 Producer Price Model. The model was run using $1 million United States dollars (USD) of economic activity in the overall wine sector. Data with respect to water consumption and solid waste disposal were provided by [12] (Tables 1 and 3). The processes within the system boundary were separated into four parts, encompassing vine planting, wine making, bottle manufacture, and wine distribution. All the impact data for these four stages were analyzed, and the contribution to the total impact of each was calculated (Tables 1–3).

Table 1. Data inventory for energy and water consumption for various stages of wine making per functional unit *.

	Vine Planting	Wine Making	Bottle Manufacture	Distribution
Energy (kJ) *	10.0	26.8	8.9	6.4
Water (gal) **	7.4	34.5	11.7	6.5

* Data based on running EioLCA [23]; one functional unit = one 750-mL bottle. ** Data based on [12].

Table 2. Data inventory for greenhouse gas emissions (g $CO_{2eq.}$) for various stages of wine making per functional unit *.

GHG *	Vine Planting	Wine Making	Bottle Manufacture	Distribution
CO_2	24.1	28.3	40.7	33.6
CH_4	0	0	0	0
N_2O	37.9	0	0	0
HFC/PFCS	0	0	0	0
Total (g CO_{2eq})	62	28.3	40.7	33.6

* Data based on running EioLCA [23]; all greenhouse gas components in the table were converted to a consistent basis of g CO_{2eq}; one functional unit = one 750-mL bottle; GHG = greenhouse gas.

Table 3. Data inventory for solid waste disposal (g) for various stages of wine making per functional unit *.

Constituent	Vine Planting	Wine Making	Bottle Manufacture	Distribution
Nitrate	0.48	0	0	0
Sulfur	2.21	0	0	0
Glyphosate	0.17	0	0	0
Mancozeb	0.24	0	0	0
Dimethomorph	43.13	0	0	0
Metiram	0.24	0	0	0
Copper oxychloride	0.23	0	0	0
Marc and lees	0	270	0	0
Stalks	0	50	0	0
Glass	0	0	170	0
Total	46.7	320	170	0

* Data based on [12]; one functional unit = one 750-mL bottle.

2.2. Techno-Economic Analysis (TEA)

The TEA accounted for all production costs, and was conducted for the key wine production processes, including vine planting and wine making. Assuming land cost was not necessary (we assumed that the land was already owned), part-time labor cost was $10/hour/person, full-time labor cost was $40,000/year/person, grape vines were 100% recycled so no cost was allocated, and grape output was assumed to be six tons/acre/year. Assuming wine output was 120 gal/ton of grapes, the useful life of all the equipment was 15 years, diesel fuel price was $3/gal, no pesticide was applied during vine cultivating, and the post-factory (i.e., at the point of sale) sales price for a bottle of wine was $10/750-mL bottle.

All relevant data of the wine production processes were collected based on three scales of wine production: small (5000 gal per year), medium (50,000 gal per year), and large (500,000 gal per year); data for the TEA were obtained from [20,24–26] (summarized in Table 4).

Table 4. Data inventory used for techno-economic analysis of various production scales [1].

Scale		Small (5000 gal/year)	Medium (50,000 gal/year)	Large (500,000 gal/year)
Land (acre)		7	70	700
Grape output (ton)		42	420	4200
Tillage *	Amount of machine	1	5	20
	Machine work time (h)	47.2	95	236
	Fuel consumption (gallon/h)	0.25	1.25	5
	Work efficiency (m^2/h)	600	3000	12,000
	Machine cost ($/machine)	500	500	500
Fertilizer *	Amount of fertilizer (lb)	105	1050	10,500
	Fertilizer cost ($/ton)	300	300	300
Harvester **	Amount of machine	1	1	1
	Machine work time (h)	3	30	300
	Fuel consumption (gallon/h)	4.8	4.8	4.8
	Work efficiency (ton/h)	14	14	14
	Machine cost ($/machine)	170,000	170,000	170,000
Fermentation tank cost ($) *		40,000	230,000	900,000
Oak barrel ***	Unit cost ($/gallon)	15	15	15
	Total cost ($)	75,600	756,000	7,560,000
Bottling equipment cost ($) ****		7000	130000	500,000
Bottle cost ***	Unit cost ($/750-mL bottle)	0.5	0.5	0.5
	Total cost ($)	12,700	127,000	1,270,000
Crush, press, rack, filter equipment cost (dollar) ****		15,000	80,000	500,000
Full time employee or wine making process (person) ****		2	3	22

[1] All values were determined based on the noted data sources. * [24]. ** [25]. *** [26]. **** [20].

The TEA was conducted for all three wine production scales. Annual costs for each scale were calculated, and were divided into three parts, which included labor costs, equipment and material costs, and costs for purchasing the wine bottles. The contribution to total annual cost of each component was assessed, while the relationship of each cost vis-à-vis each production scale was analyzed. Annual revenue for each scale was calculated, and then the relationships among all three scales were assessed. Annual net profits for each scale were calculated. Finally, break-even unit price (i.e., price per 750 mL bottle) was calculated as shown in Equation (1).

$$\text{Break-even unit price (US \$/ bottle)} = \text{annual production cost (US \$/year)} / \text{annual output (mL/year)} \times 750 \text{ mL/bottle} \quad (1)$$

3. Results and Discussion

3.1. Life-Cycle Assessment (LCA)

In terms of energy consumption, bottle manufacturing and the wine making itself contributed the most impact, which accounted for 35% and 31%, respectively (Figure 2). Compared to vine planting and wine distribution, the processes of bottle manufacturing and wine making were likely more complex, which resulted in higher energy consumption compared to vine planting and wine distribution.

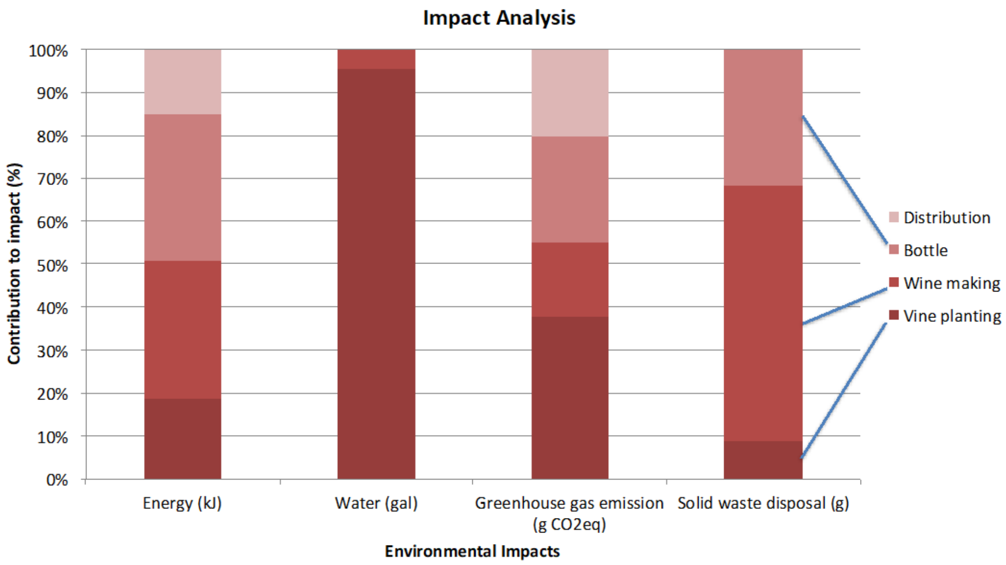

Figure 2. Allocation of environmental emissions to various segments of the wine life cycle.

For water consumption, wine making contributed the greatest impact, accounting for 91% of all water consumption (Figure 2), and was likely due to water used for fermentation, cleaning, etc. All other portions of the supply chain (Figure 1) consumed only 9% of the water used to produce each bottle of wine.

Vine planting and bottle manufacturing accounted for the most greenhouse gas emissions from the system, accounting for 38% and 25%, respectively (Figure 2). Bottle manufacture and wine making accounted for the majority of solid waste disposal, accounting for 32% and 59%, respectively (Figure 2).

Fusi et al. conducted a "cradle-to-grave" LCA (i.e., a total LCA) to identify and assess the environmental burdens for white-wine production, including grape planting, wine production, wine bottling, packaging, distribution, and disposal of the wine bottles [12]. They concluded that the glass-bottle production was the most detrimental to the environmental performance of white-wine production, and our present study achieved a similar conclusion. Additionally, they determined that the wine-making stage also resulted in critical impacts on the environment, which are reflective of our results as well.

3.2. Techno-Economic Analysis (TEA)

Annual costs, revenues, and profits were calculated for each production scale (Table 5). As expected, the annual costs increased when the production scale increased (Figure 3). The relationship amongst annual cost for small (5000 gal per year), medium (50,000 gal per year), and large (500,000 gal per year) followed an exponential increase, with an R^2 value equal to 0.93 (Figure 4). It appears, however, that a linear increase fit the results better, with an R^2 = 0.99 (Figure 5). When the production scale increased, the contribution of labor cost decreased (due to efficiencies of scale), but the contribution of cost of purchasing wine bottles increased (Figure 6), which was anticipated.

Table 5. Annual economic results from techno-economic analysis of various production scales.*.

Scale		Small (5000 gal/year)	Medium (50,000 gal/year)	Large (500,000 gal/year)
Grape vine	Recycle	0	0	0
	Labor	472	950	2360
Tillage ($/year)	Machine	33	167	700
	Energy	36	360	3600
Fertilizer ($/year)		14	140	1400
	Labor	30	300	3000
Harvest ($/year)	Machine	12,000	12,000	12,000
	Energy	43.2	432	4320
Fermentation tank ($/year)		2700	15,500	60,000
Oak barrel ($/year)		5040	50,400	504,000
Bottling equipment ($/year)		470	8700	35,000
Bottle ($/year)		12,700	127,000	1,270,000
Crush, press, rack, filter equipment ($/year)		1000	5400	35,000
Labor cost for full time employee ($/year)		80,000	120,000	880,000
Cost of equipment and material ($/year)		21,336	93,099	656,020
Cost of labor ($/year)		80,502	121,250	885,360
Cost of bottle ($/year)		12,700	127,000	1,270,000
Total cost ($/year)		114,587	341,839	2,816,280
Revenue ($/year)		252,360	2,523,600	25,236,000
Net profit ($/year)		137,773	2,181,761	22,419,720

* All values were calculated based on the data provided in Table 4.

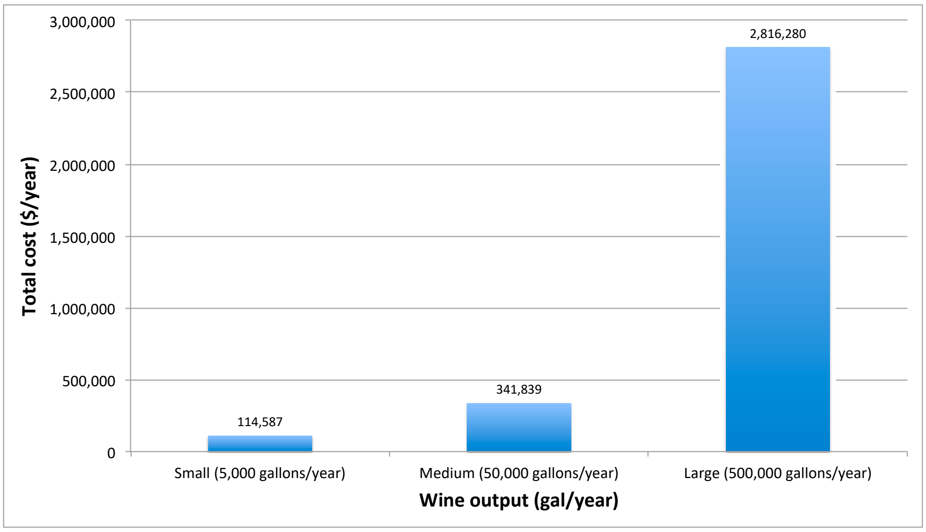

Figure 3. Total annual production costs according to scale of operation.

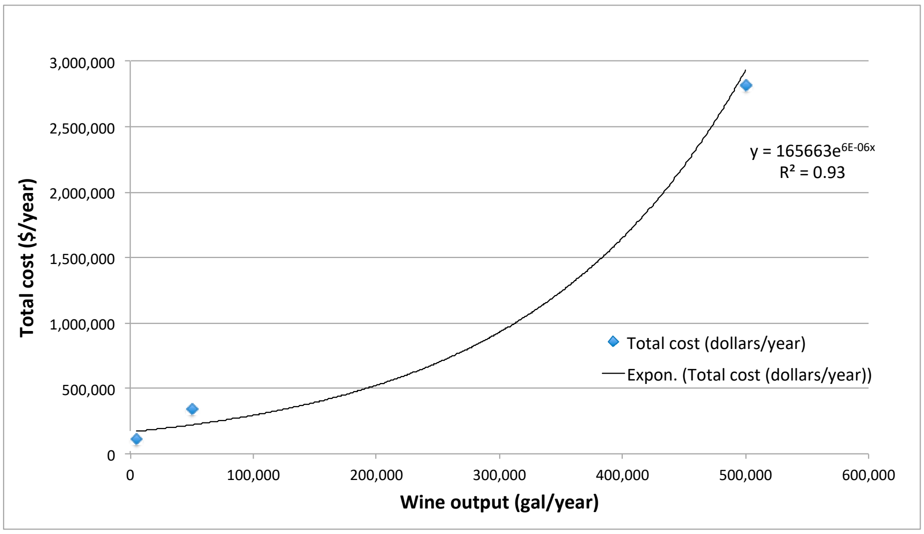

Figure 4. Annual production costs according to scale of operation (showing exponential trendline).

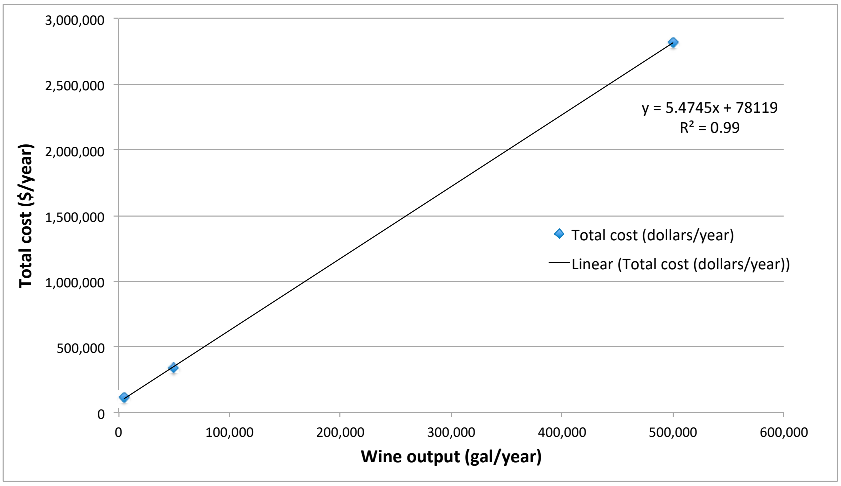

Figure 5. Annual production costs according to scale of operation (showing linear trendline).

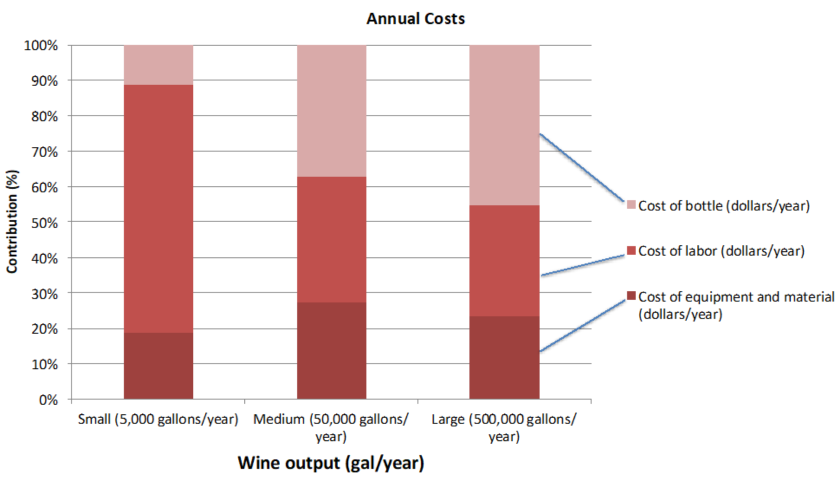

Figure 6. Allocation of annual production costs, according to type of cost and production scale. Note that many costs are impacted by economies of scale.

Annual revenues, similar to annual costs, increased when the production scale increased (Figure 7). The relationship between annual revenue and production scale could be explained by an exponential fit, with an $R^2 = 0.82$ (Figure 8). However, as shown in Figure 9, the increase was better explained using a linear fit, with an $R^2 = 0.99$. This was likely due to revenue being calculated purely based on production scale.

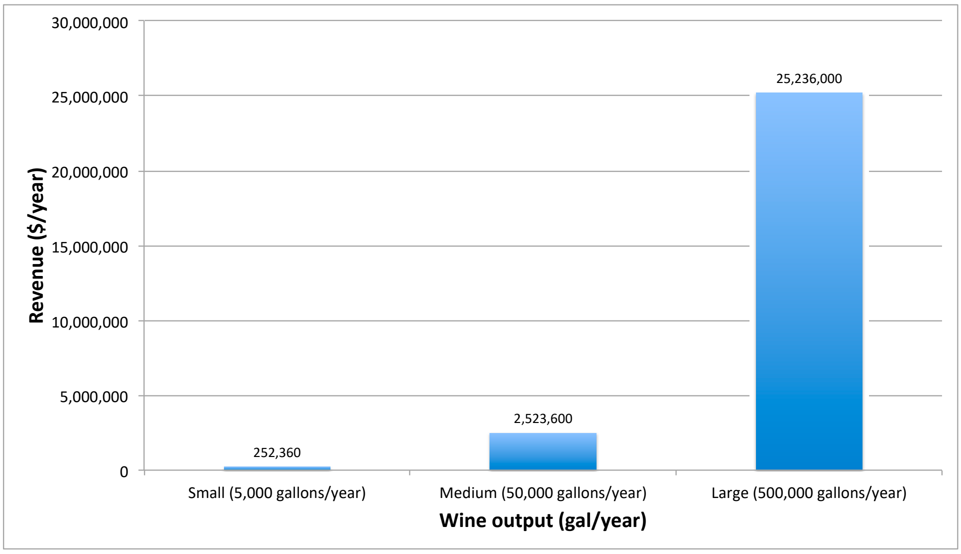

Figure 7. Annual revenues according to scale of operation.

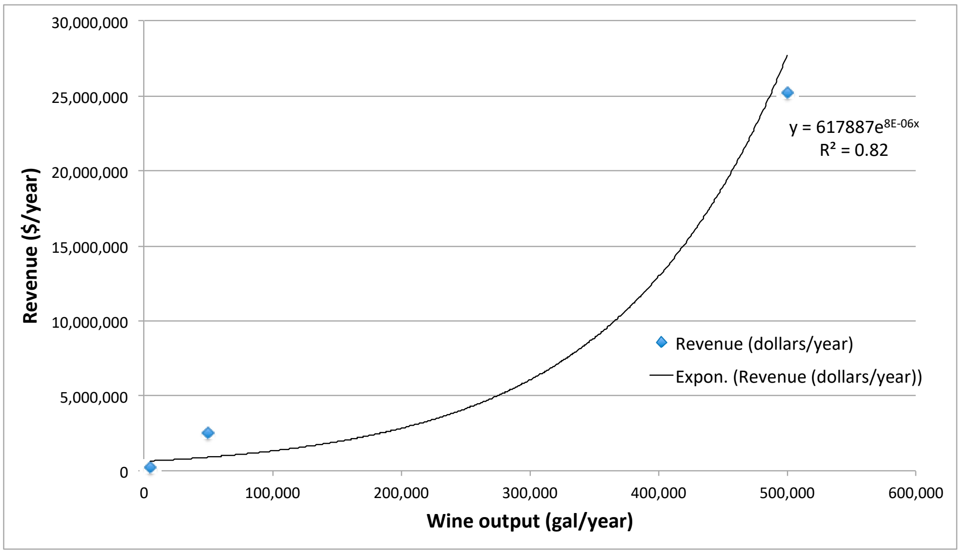

Figure 8. Annual revenues according to scale of operation (showing exponential trendline).

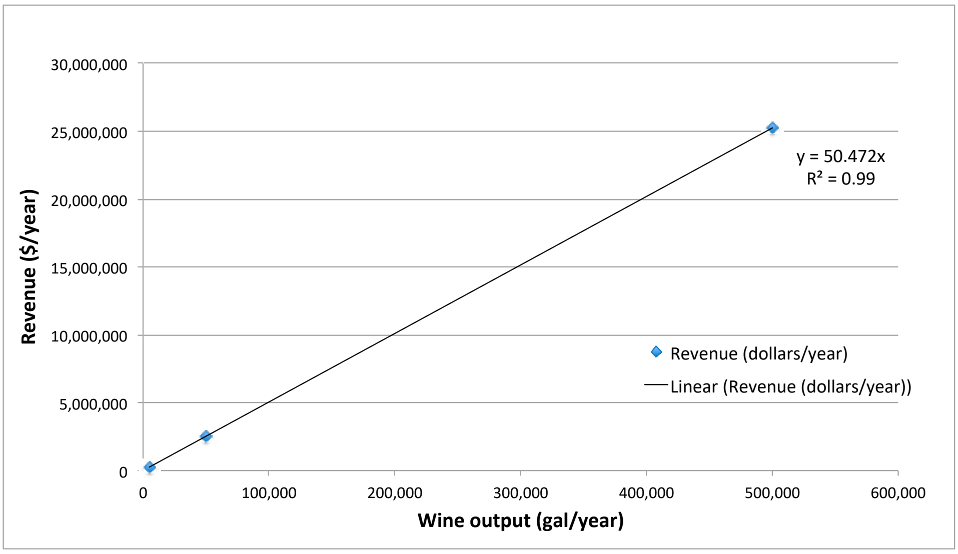

Figure 9. Annual revenues according to scale of operation (showing linear trendline).

Annual profits, which are a function of annual costs and revenues, increased when the production scale increased (Figure 10). The relationship between annual profits and production scale exhibited an exponential increase (R^2 = 0.78, Figure 11); however, as shown in Figure 12, a linear fit was a better descriptor (R^2 = 0.99). This was likely due to annual profits being more affected by annual revenues than by annual costs, as the amount of annual revenue was considerably higher than that of annual costs.

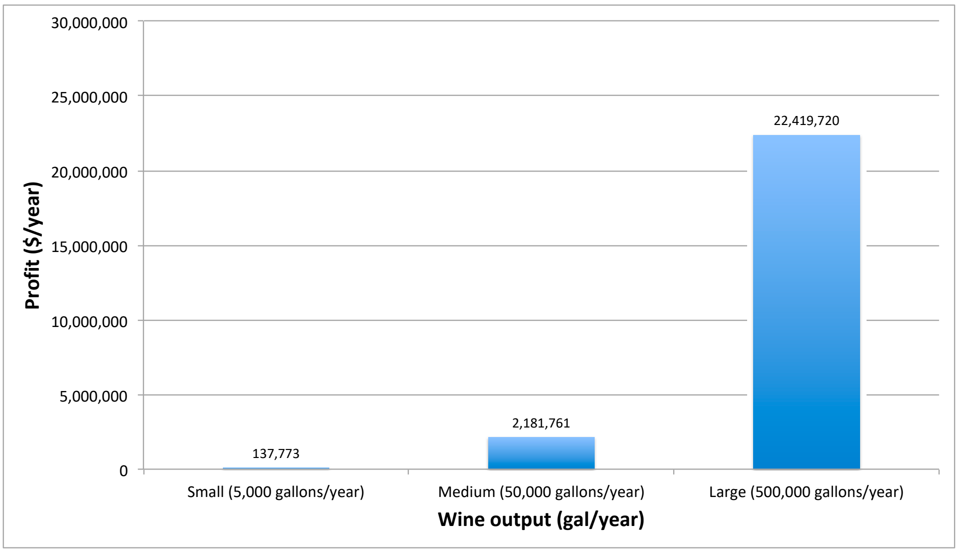

Figure 10. Annual net profit according to scale of operation.

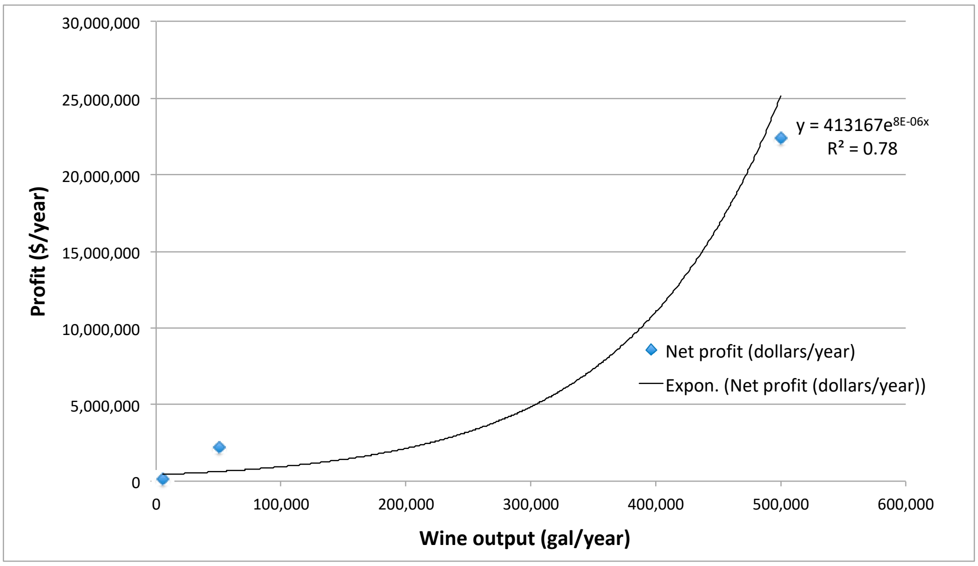

Figure 11. Annual net profit according to scale of operation (showing exponential trendline).

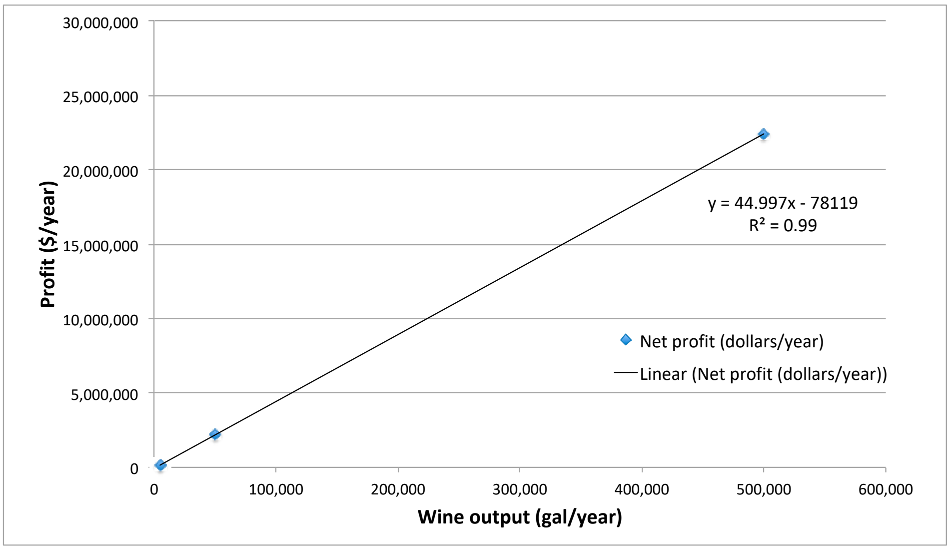

Figure 12. Annual net profit according to scale of operation (showing linear trendline).

For the break-even price assessment, based on the total costs and outputs for each production scale, the relationship between net profit and unit price could be calculated (Figure 13). The break-even price was $4.54/750-mL bottle for 5000 gal/year production, $1.35/750-mL bottle for 50,000 gal/year production, and $1.12/750-mL bottle for 500,000 gal/year wine production. These results clearly showed that the larger the winery production size is, the lower the required break-even price becomes.

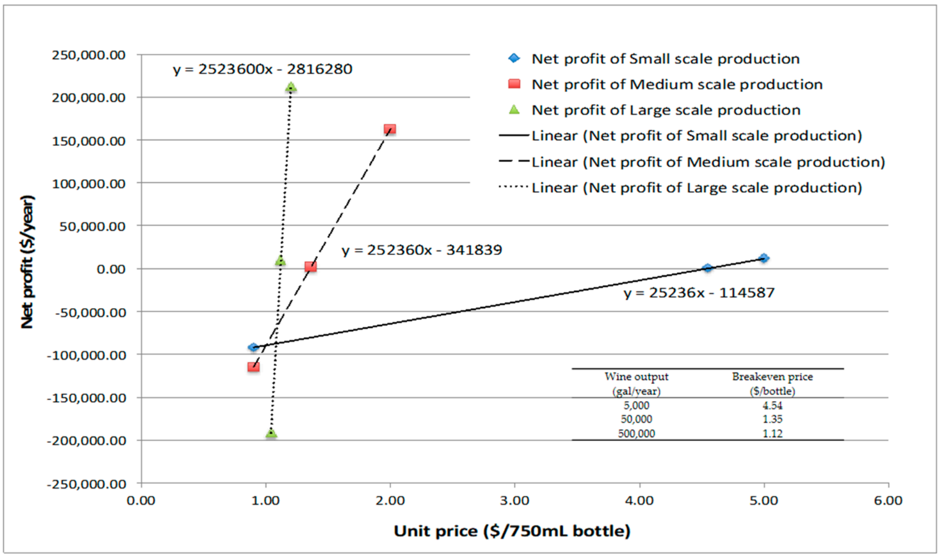

Figure 13. Estimated net profit and break-even price (where each profit trend line crosses the *x*-axis) according to scale of operation. Note that the larger the production scale is, the faster the break-even price is achieved.

Dillon et al. developed an economic decision-making model for small to medium-sized wineries, and determined that the larger the winery size is, the lower the required break-even price becomes [20]. Our study achieved similar break-even results, as we determined that there was an increase in profit when the winery size increased, which could be described using either an exponential or linear trend. Dillon et al. [21] determined that the cost of the raw materials had the most substantial effect on annual costs; our study, on the other hand, found that the cost of labor and bottle purchasing costs contributed the most to the total cost (Figure 6).

3.3. Implications

From our LCA and TEA modeling, it appears that more efficient bottle-manufacturing and wine-making processes could be effective targets for reducing energy and water consumption, as well as solid waste disposal. Additionally, vine planting and bottle manufacturing could be effective targets for reducing greenhouse gas emissions.

Since the annual cost of purchasing wine bottles represented the greatest contribution to annual operating costs for the large-scale winery, steps to reduce these costs could be pursued, including manufacturing their own glass bottles (as some large wineries do) and, therefore, potentially increasing net profit. However, further economic analysis is needed to clarify this.

Even though they were not examined in this study, other alternative ways of producing wines that can lessen environmental impacts and potentially improve economic efficiencies should also be examined. For example, there are now many opportunities to produce lighter glass bottles, changing adhesives, labels, and closures, producing alternative energy at the winery (e.g., solar, wind, anaerobic digestion, etc.), reducing packaging materials and wastes, and implementing recycling programs. Also, there is growing interest in organic farming systems for viticulture.

Indeed, there are many opportunities that are being implemented in vineyards and wineries to help improve the sustainability of specific businesses, as well as the entire wine industry overall. These new techniques and technologies should be examined using life-cycle assessment and techno-economic analysis in order to understand environmental and cost impacts vis-à-vis traditional approaches.

4. Conclusions

Production scale of wine production matters both for environmental impacts and costs. In terms of life-cycle assessment, bottle manufacture and wine making contributed the greatest share of energy consumption, while wine making was the greatest in terms of water consumption. For the output impacts, vine planting and bottle manufacture contributed the most to greenhouse gas emissions, while bottle manufacture and wine making contributed the most to solid waste disposal. Regarding techno-economic analysis, the relationships amongst annual costs for small (5000 gal per year), medium (50,000 gal per year), and large (500,000 gal per year) wine production exhibited a moderate exponential increase, although a linear increase appeared to fit better. The labor cost contribution to total costs decreased when production size increased, while the bottle cost contribution to total costs increased when production size increased. The annual revenues for small, medium, and large production scales also followed a moderate exponential increase, but a linear increase fit the data better. Again, the relationship between annual net profits and production scale was best described using a linear trend. The break-even prices were $4.55, $1.36 and $1.12/750-mL bottle for winery sizes of 5000, 50,000, and 500,000 gal/year; the larger the winery size is, the lower the required break-even price becomes. Further research is needed in order to optimize productivity, increase efficiencies, reduce environmental impacts, and minimize costs.

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