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Life cycle assessment (LCA) of nanocellulose composite panels (NCPs) manufactured using freeze-drying technique

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Abstract

The life cycle assessment (LCA) is a powerful technique to investigate the environmental impacts of current and new products and production processes. In this research, the LCA of nanocellulose composite panels (NCPs) produced using freeze-drying techniques were studied. The environmental effects of the final product and the production method were reported. The nanocellulose is a bio-based raw material that can be obtained from a variety of natural sources and used in building, construction, packaging, pharmaceutical, and insulation industry. The wood-based cellulose nanofibrils (CNF) produced using mechanical grinding, and the industrial corn-starch (Ethylex 2025) were used as raw materials in this study. The n-Dodecenyl Succinic Anhydride (DDSA) and boric acid (BA - (($B(OH)_3$) - 99.94 % pure) were used as treatment materials. As a result of this explanatory research, the cellulose nanofibrils (CNFs) produced using mechanical process were found environmentally friendly as expected. The production process, freeze-drying technique, was not found eco-friendly in laboratory scale. However, using solar energy in full-scale production can decrease the energy consumption up to 76% and would make the process eco-friendlier. The nanocellulose composite panels (NCPs) can be produced using the freeze-drying technique. The findings of this study showed that freeze-drying technique would be feasible and nature-friendly in full-scale production using renewable energy sources.

Keywords: Life Cycle Assessment (LCA), wood based material, nanocellulose, composite panels, freeze-drying

Dondurarak-kurutma yöntemi ile üretilmiş nanoselüloz kompozit panellerin yaşam döngüsü değerlendirmesi (YDD)

Öz

Yaşam döngüsü değerlendirme (YDD) yöntemi malzemelerin çevreye etkilerini incelemekte etkin bir araçtır. Bu çalışmada, dondurarak-kurutma yöntemi ile üretilmiş nanoselüloz kompozit panellerin (NKP) YDD'leri incelenmiştir. Son ürün ve üretim aşamalarının çevreye etkileri belirlenmiş ve raporlanmıştır. Nanoselüloz, biyo bazlı çevreye zararı olmayan ve doğada birçok kaynaktan elde edilebilen, ambalajlama, inşaat, yapı ve benzeri endüstrilerde kullanılan doğal bir polimerdir. Bu çalışmada mekaniksel yöntemlerle odun malzemeden üretilmiş selüloz nanolifler (SNL), endüstriyel mısır nişastası (MN), Dodecenyl Succinic Anhydride (DDSA) ve borik asit (BA - (($B(OH)_3$) - % 99.94 saflık) kullanılmıştır. Araştırmaya dayalı bu çalışmanın sonucunda, odun malzemeden üretilmiş selüloz nanolifler kullanılarak üretilen malzemelerin beklendiği gibi çevreci malzemeler olduğu belirlenmiştir. Dondurarak-kurutma yönteminin ise laboratuar ölçeğinde kullanımı çevreci bulunmamıştır. Yapılan ek incelemeler ve araştırmalar; tam ölçekli üretimde, yenilenebilir enerji kaynaklarının kullanılması durumunda % 76'lık bir iyileştirme olabileceğini göstermiştir. Selüloz nanolif bazlı kompozit malzemelerin dondurarak-kurutma yöntemi ile üretilmesi; tam ölçekli üretim kullanılması ve de yenilenebilir enerji kaynaklarının kullanılması durumunda çevreci bulunmuştur.

Anahtar Kelimeler: Yaşam Döngüsü Değerlendirmesi (YDD), ahşap esaslı malzeme, nanoselüloz, kompozit panel, dondurarak kurutma

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1. Introduction

Life-cycle assessment (LCA) is a comprehensive technique to analyze the potential effects of products and processes that might have on the environment (Puettmann et al., 2016a; Chin et al., 2016). Many studies were performed since the 1960s to evaluate the cumulative energy demand to design and manufacture new products (Fava and Page, 1992). LCA's mission is to evaluate the potential impacts to the environment through the production and use of these product's life cycle. LCA tool is capable of investigating products' full production processes (cradle to grave), or capable of focusing only a pre-determined portion (cradle to gate) (Puettman et al., 2009). LCA is defined as a multiphase process consisting of following steps (Fig. 1) (ISO, 2006). The LCA steps (Figure 1.), components of the LCA, are connected to each other and the outcomes of the project are dependent on the overall project purpose.

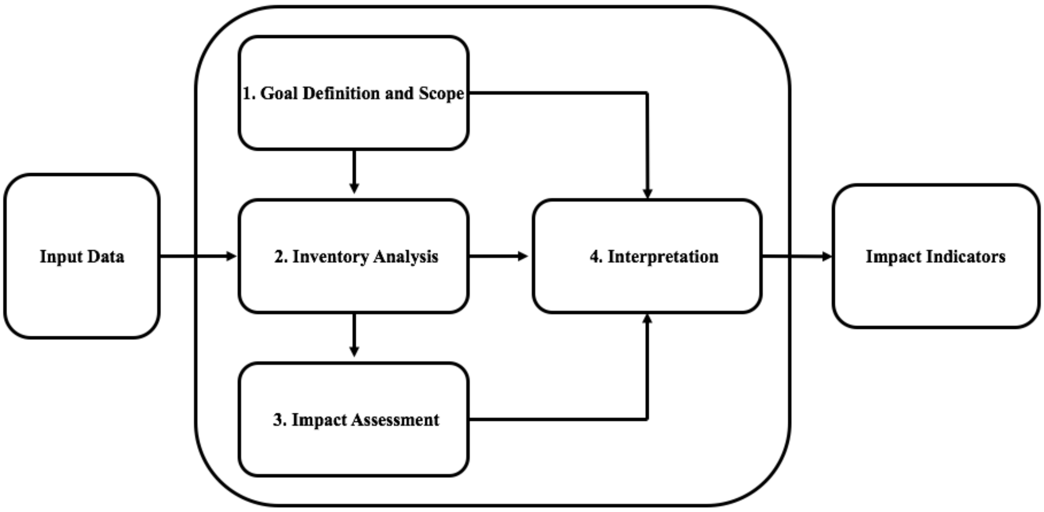

Figure 1. Life cycle assessment (LCA) steps
Şekil 1. Yaşam döndüsü değerlendirme (YDD) adımları

LCA is becoming more critical with the increased environmental awareness in many industries. The environmental impacts, types of energy, and overall embodied energy are very critical attributes in building materials used today (Qarout, 2017). During the life cycle of an average building, energy used for heating and cooling represents the largest use from cradle to grave, also representing the greatest opportunity for energy reductions. The thermal insulation foams can provide energy savings equivalent to heating and cooling up 56 million households or operate 135 million cars annually (URL-1).

Nowadays, green certification programs that credits the building or materials are offered in many countries (LEED - Leadership in energy and Environmental Design) (URL-2). The points from crediting can be achieved based on recycled content (10-20%) (1-2 pts), use of materials extracted and produced (10-20%) within 500 miles radius (up to 10 pts), and energy performance (1-10 pts). Similar systems can be found in other countries.

Most rigid foam insulation products available today are primarily made from petroleum-based materials. The development of insulation made from renewable materials that support green building criteria, such as LEED, can provide customers with energy benefits during use in addition to the overall reduced embodied energy of the product. The purpose of this research is to perform life cycle assessment of a cellulose nanofibrils (CNFs) and corn-starch (CS) based insulation material referred to here as nanocellulose composite panel (NCP). The inputs and the outputs used for modeling the production of NCP are primary data based on a lab-scale manufacturing process.

NCP made from biopolymers can be classified as a renewable material to be used in buildings. CNF is a type of nanocellulose and can be obtained from natural sources (Moon et al., 2010). Corn-starch is another environmentally friendly polymer that is commonly used in many industries including food, packaging, and pharmaceutical (Dale, 2003). CNFs have strong ability to reinforce otherwise weak panel materials, enabling the development of new composite products with enhanced performance properties such as insulating attributes (Yildirim et al., 2014). Although being an abundant and environmentally friendly polymers, CNF and CS both have drawback properties; flammability and hydrophilicity (Lavoine et al., 2012) that limits the usage of these polymers in many potential industry applications (Bayer et al., 2011).

In this research, the life cycle assessment (LCA) of an environmentally-friendly NCPs treated with boric acid (BA - (B(OH)3) - 99.94 % pure) (Horrocks et al., 2005; Alongi and Malucelli, 2015) against flammability and the n-dodecenyl succinic anhydride against water adsorption (N-DDSA) (Salminen, 2012) were studied.

The overall purpose of this study was to determine cumulative energy demand (CED) and environmental impacts associated with the production of NCPs using the freeze-drying technique. The data were obtained through a laboratory-scaled production process. Table 1 lists the physical properties of the lab-scale NCP.

Table 1. Physical properties of NCP used for the LCA
Tablo 1. YDD'si yapılan NCP'nin fiziksel özellikleri

NCP Product	Meters
Width	0.24
Length	0.49
Thickness	0.02
Mass/area	1.32 kg/m^2, 1.47 cm basis
Density	89.58 kg/m^3
R-value	3.10 – 3.50

2. Materials and Method

The softwood cellulose nanofibrils (CNF) produced through mechanical grinding without chemical treatment, and the industrial corn-starch (Ethylex 2025) purchased from Tate&Lyle were used as raw materials in this study. The n-Dodecenyl Succinic Anhydride (DDSA) (Vertellus Inc. The United States) and the boric acid (BA - ($(B(OH)_3)$ - 99.94% pure) (Rose Mill Co. The United States) was used as ancillary materials.

This study invesitigates 'cradle to gate' LCA to produce NCP using resources and material common to North America. This study was performed according to following laboratory location; Nutting Hall, University of Maine, Orono, ME, United States. It covers the impacts regarding input materials and electricity through to the outputs of the NCP product and emissions. The following investigations were performed under this study;

2.1. Life cycle inventory (LCI)

The life cycle inventory is a data-based process that quantifies raw material and energy requirements, solid waste, air emissions, waterborne effluents, and other environmental releases occurring within the pre-determined system boundaries.

2.2. Life cycle impact assessment (LCIA)

The TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) impact technique were used, which is a midpoint oriented LCIA methodology developed by the U.S. Environmental Protection Agency (EPA) (Bare, 2011). TRACI was available through the LCA software used for modeling NCP process (URL-3).

2.3. Life cycle interpretation

The life cycle interpretation investigates the findings of either the LCI or the LCIA, or both, and evaluates in relation to the defined goal and scope to reach conclusions and recommendations.

2.4. Functional unit

In this LCA study, the functional unit was 1 m^2 of insulation material with a thickness of 0.578 inches (0.015 m). One (1) m^2 was equal to 1.315 kg.

2.5. System boundaries

The planting gowth was followed by the harvest of the softwood trees destined for a pulp mill, and ends with the final NCP products (cradle to gate). The extraction module includes forest regeneration and stand management, if any, felling the trees with a feller buncher, processing the trees by removing limbs, and cutting to shipping lengths, and transportation of logs to landing using a skidder. The extraction modules; maintenance and repair of equipment, and building and maintenance of logging roads, logging camps, and weigh stations were excluded.

Pulp production represents average North American production (URL-4). The process includes pulp production from wood and drying. Purchased energy is included and upstream flows associated with its generation. Product transportation is included as reported for NCP production. Air emissions from process sources are included along with emissions related to the combustion of fuels used in pulp production and upstream processes.

NCP production (Figure 2) includes primary data received according to lab-scale process. Data for the process included electricity, chemicals and raw materials. The cradle to gate outputs include 1 m^2 of NCP ready to be shipped, air and water emissions, and solid waste.

2.6. Data sourcing

The LCA for NCP contains the production of softwood pulp (cellulose nanofibrils), the production of chemicals and ancillary materials, production of electricity and fuels, and transportation of inputs to the NCP production facility. Primary data was collected to produce NCP, and secondary data sources were used for all other materials, energy and transportation (Table 2).

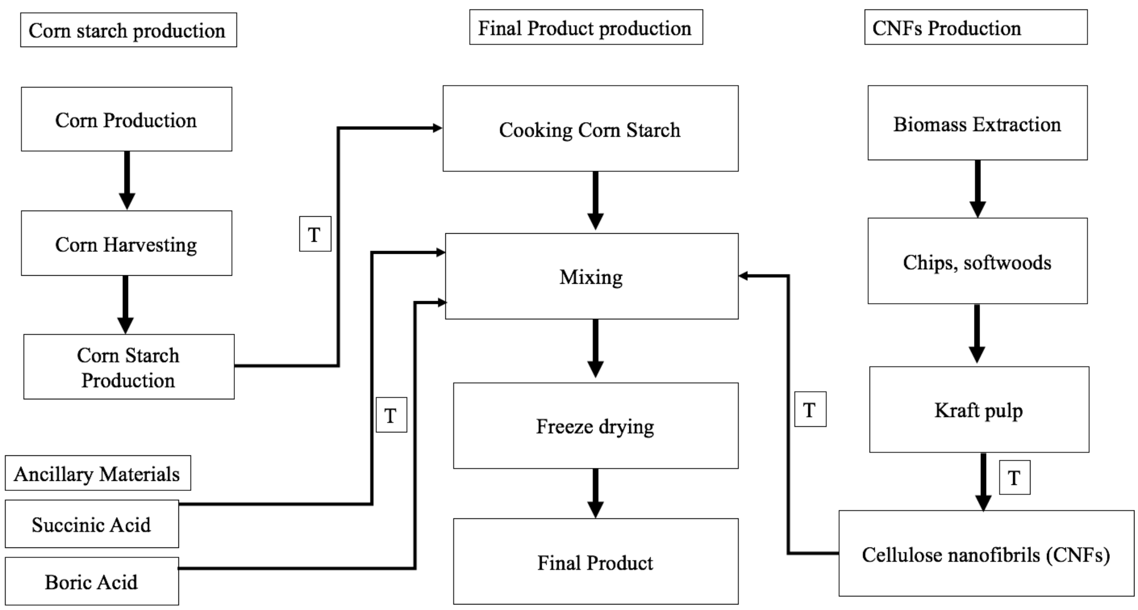

Figure 2. The process flow for the production of NCP. (T: Transportation)
Şekil 2. NCP üretimi akış diagramı. (T: Ulaşım)

Table 2. Secondary LCI data sources used to model the cradle to gate LCA for NCP production

Tablo 2. NCP'nin beşikten - kapıya YDD'si yapılırken kullanılan ikincil yaşam döngü envanteri veri bankası

Process	Reference
Diesel truck	(URL-5)
Electricity	(Puettmann, 2000)
Electricity- Maine	(Puettmann et al., 2012)
Wood residue production	(Puettmann et al., 2016b)
Kraft Pulp	(Dunn et al., 2015)
Corn-starch	(URL-5)
Boric Acid	(Puettmann, 2000; Puettmann et al., 2016b)
Succinic acid	(Dunn et al., 2015)

LCIA phase created a bridge between the LCI results and expected environmental impacts as mentioned earlier in this study. The LCIA calculated the impact indicators (global warming potential, smog). These impact indicators provide general, but quantifiable, indications of potential environmental impacts. The target impact indicator, the impact category, and means of characterizing the impacts are summarized in Table 3. Environmental impacts are determined using the TRACI method (Bare, 2011).

The selected impact indicators are given in Table 3. It showed the measure of an aspect of a potential impact. The life cycle assessment (LCA) performed under this study investigated the environmental impacts and the cumulative energy demand of a novel, environmentally-friendly NCPs as an alternative to fossil-based insulation materials used in building construction.

3. Results

3.1. Resource and material transport

The material transportation was provided by a truck. The transportation distances were regionally based (<1000 miles (1609 km)) except for corn-starch (Table 4). The inputs to the transportation process was diesel fuel and the outputs were emission to air and water and solid waste generated from the production and combustion of the fuel.

3.2. Electricity generation

Energy to produce NCP (on-site) comes exclusively from electricity. Emission resulting from the production of electricity were a grid composition for the New England region of the U.S. (Table 5). Two other electricity sources were evaluated: 1. Maine electricity generation, and 2. 100% solar energy for production of NCP.

As it was proposed in Table 5, the NCP could be manufactured using 100 percent solar energy. If this is the case, solar energy provides a 76% reduction from the current electricity use using the NEWE grid and a 43% reduction from the Maine electricity after 50% electricity reduction is applied.

Table 3. Pre-determined impact indicators, characterization models and impact categories.
Tablo 3. Önceden belirlenmiş etki indeksleri, modellemeleri ve etki kategorileri

Impact Indicator	Characterization Model	Impact Category
Greenhouse gas (GHG) emissions	The total emissions in the reference unit of carbon dioxide (CO_2) equivalents for CO_2, methane, and nitrous oxide.	Global warming
Releases to air decreasing or thinning of ozone layer	ozone-forming chemicals (chlorofluorocarbon (CFC's) hydro chlorofluorocarbon (HCFC's) chlorine (Cl) bromine (Br)) in the stratosphere. Ozone depletion values are measured in the reference units of CFC equivalents.	Ozone depletion
Releases to air potentially resulting in acid rain (acidification)	Calculate total sulfur dioxide (SO_2) equivalent for releases of acid-forming chemicals such as sulfur oxides (SOx), nitrogen oxides (NOx), hydrochloric acid (HCl), and ammonia (NH_3). Acidification value of SO_2 is used as a reference unit.	Acidification
Releases to air potentially resulting in smog	Calculate total substances that can be photo-chemically oxidized. The smog-forming potential of ozone (O_3) is used as a reference unit.	Photochemical smog
Releases to air potentially resulting in eutrophication of water bodies	Calculate total substances that contain available nitrogen or phosphorus. Eutrophication potential of N-eq. is used as a reference unit.	Eutrophication
Non-renewable, fossil	Coal bituminous, coal brown, coal hard, natural gas, methane, oil crude, peat	-
Non-renewable, nuclear	Uranium, uranium ore, energy from uranium	-
Non-renewable, biomass	Energy, gross calorific value, in biomass, primary forest	-
Renewable, biomass	Wood, biomass	-
Renewable, wind, solar, geothermal	Energy from geothermal, wind, solar	-
Renewable, water	Hydropower	-

The Cumulative Energy Demand (CED) calculated using the impact method by Frischknecht et al. (Frischknecht and Jungbluth, 2003) are given in Table 6. Total energy for the current use, NCP, 50 percent electricity reduction using NEWE, Maine and solar is; 989 MJ/m^2, 47 MJ/m^2, 514 MJ/m^2, 410 MJ/m^2 and 235 MJ per m^2, respectively.

3.3. Environmental categories

Cradle to gate LCIA of NCP under three electricity scenarios is shown in Table 7. Looking only at 50 percent electricity reduction option, solar energy generation profiles the best environmental choice.

In most situations (Table 7), the impact shifts from one category to another. A good example is compa-

Table 4. One-way transportation distances for raw and anchillary materials for NCP production
Tablo 4. NCP üretimi için gerekli olan tek yön ulaşım mesafeleri

Material	From:	To:	miles	km	Manufacture
Wood Residue	Forest road	Pulp mill	435	700	From database
Kraft Pulp	Saint Felicien, Quebec, Canada	Orono, ME	413	665	Resolute Forest Products
Corn-starch (Ethylex 2025)	Decatur, IL	Orono, ME	1,361	2,190	Tate and Lyle
Boric acid	West Hartford, CT	Orono, ME	342	550	Rose Mill Co.
Succinic acid	Delaware Water Gap, PA	Orono, ME	519	835	Vertellus

ring the NEWE and Maine electricity grids. There is a decrease from 27% to 45% in all categories except for smog, which increases by 216% under the Maine electricity scenario. Further examination into this impact category showed that the increase was a result of higher renewable biomass used in Maine electricity production. The switch to the solar model, resulted in decreases in all impact categories from 71% to 97% (Table 7).

Table 5. Allocation of fuel sources for electricity generation for the New England grid, Maine electricity generation, and proposed for NCP production.
Tablo 5. NCP üretimi için gerekli olan alternatifli enerji kaynaklarının üretiminde kullnılan yakıt yüzdeleri.

Fuel Source	NEWE Electricity Grid	Maine Electricity Generation	NCP Production Goal
Natural gas	41.17%	37.79%	0
Nuclear	28.26%	0.00%	0
Coal	11.22%	0.60%	0
Diesel	6.80%	-	0
Other	6.21%	3.06%	0
Hydro	5.39%	27.355	0
Residual fuel oil	0.67%	2.30%	0
Wind	0.29%	8.28%	0
Solar	0.00%	0.00%	100%
Wood		24.07%	0
Other Biomass		1.55%	0

3.4. Treatment of biogenic carbon

Treatment of biogenic carbon is consistent with the Intergovernmental Panel for Climate Change (IPCC) (Simon et al., 2006) inventory reporting framework.

The approach to the treatment of biogenic carbon was taken for the Norwegian Solid Wood Product PCR (Aasestad, 2008), and the North American PCR has adopted an identical approach to ensure comparability and consistency. The default TRACI impact assessment method was used, which did not count the CO_2 emissions released during the combustion of woody biomass during production. The complete list of emissions factors for the GWP method used can be found in Bare's study (Bare, 2011). As a result, 59 kg CO_2 eq. were released in the production of 1 m^2 of Arbolate (current electricity use and grid). That same 1 m^2 stores 0.541 kg CO_2 eq resulting in a net GWP of 44.38 (Table 8).

Table 6. Cradle to gate Cumulative energy demand (CED) for 1 square meter (m^2) of NCP.
Tablo 6. Beşikten-kapıya 1 metrekare NCP üretimi için gerekli olan toplam enerji miktarı.

	NEWE Grid			Maine Electricity	Proposed Solar
Impact Category	Current Electricity Consumption	Using NCP Electricity Rates	50% Electricity Reduction	50% Electricity Reduction	50% Electricity Reduction
			MJ/m^2		
Non-renewable, fossil	931.4200	28.53	475.65	271.09	13.86
Non-renewable, nuclear	0.0267	0.0267	0.0267	0.0267	0.0267
Non-renewable, biomass	0.0000	0.0000	0.0000	0.0000	0.0000
Renewable, biomass	34.4400	17.8600	26.0700	66.6700	17.5900
Renewable, wind, solar, geothermal	1.2000	0.0200	0.6100	16.8900	203.8800
Renewable, hydro	22.3400	0.3700	11.2500	55.7700	0.0100
Total	989.4200	46.8100	513.6000	410.4400	235.3700

Table 7. Life cycle impact assessment results for production of NCP under three alternative electricity generation scenarios
Tablo 7. NCP üretimi için gerekli olan 3 farklı enerji kaynağına göre hazırlanmış yaşam döngüsü etki değerlendirmesi sonuçları

Impact category	NCP 50% NEWE	NCP 50% Maine	NCP 50% Solar
Ozone depletion	0.0000	0.0000	0.0000
Global warming	30.2600	16.6500	1.0600
Smog	1.1900	3.7500	0.0900
Acidification	0.2343	0.1430	0.0098
Eutrophication	0.0040	0.0029	0.0011
Carcinogenic	0.0000	0.0000	0.0000
Non-carcinogenic	0.0000	0.0000	0.0000
Respiratory effects	0.0128	0.0078	0.0007
Ecotoxicity	41.1000	25.6300	4.4000
Fossil fuel depletion	57.1100	39.1500	1.6800

Table 8. Net Carbon emissions
Tablo 8. Net Karbon Salınımı

	Arbolate NEWE Current	Arbolate 50% NEWE	Arbolate 50% Maine	Arbolate 50% Solar
Released for extraction and manufacturing	44.92	30.26	16.65	1.06
CO2 eq. stored in product	0.54	0.54	0.54	0.54
Net carbon emissions (kg CO2 eq.)	44.38	29.72	16.15	0.52

4. Conclusions

The life cycle assessment (LCA) is a comprehensive technique that provides information about the potential environmental effects of the products and processes. The comprehensive analyses provide detailed information about the manufacturing process. It also offers details about the required energy and the overall costs.

In this research, the life cycle assessment (LCA) of nanocellulose composite panels (NCPs) produced using freeze-drying techniques was investigated and reported. Electricity consumption during NCP production (on-site) was the largest consumer of energy over all life cycle stages from cradle to gate. When assuming a 50% reduction in electricity consumption for the full-scale production, the following results were achieved: A reduction of 48% in total energy (cradle to gate) using the current NEWE New England regional grid, A reduction of 58% in total energy (cradle to gate) using a Maine electricity production grid, A reduction of 76% in total energy (cradle to gate) using a 100% solar energy option, GWP was decreased by 45% using a Maine electricity production grid, GWP is decreased by 97% using a 100% solar energy option.

Non-renewable fossil-based fuels were reduced by 28% when a Maine electricity grid was used. Renewable fuels (hydro and biomass) are increased by 23% when a Maine electricity grid is used. Smog impact category was increased by 216% by switching from the current NEWE grid to a Maine electricity production grid.

Consequently, using solar energy for the overall production process and being close to energy providers would produce significantly lower energy demand and would provide environmentally process and a final product.

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