# Chapter 7

# A Societal Life Cycle Costing of Energy Production: The Implications of Environmental Externalities

Yemane W. Weldu

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.77188

**Abstract**

Alberta's electricity market is deregulated; consequently, it does not recognize the benefits of renewables. This research applied a novel societal life cycle costing approach to estimate the economic values of environmental damages to society that result from coal and biomass fired electricity generation. Although coal fuel is cheaper to produce electricity, yet its societal life cycle costing (LCC) is significantly higher than bioenergy systems. Mainstreaming of environmental externalities creates market advantages for low carbon energy sources. Coal power plants cause Alberta to lose at least $117.8 billion per annum due to externalities. Ending electricity from coal with wood pellet can save 53.7 billion USD per year. The societal life cycle cost per year of coal power plants in Alberta represents 15.8% of the province's GDP and 343.7% of the total expenditure on health. The transformative potential presented by carbon pricing toward a cleaner future is limited. Externalities for health and ecosystems should also be priced and included in the retail price of electricity.

**Keywords:** externality, electricity, human health, ecosystem, societal life cycle cost

## 1. Introduction

Alberta's electricity grid is fossil-intensive that more than 80% of the electricity supply is sourced from fossil fuels [1]. The provincial *Climate Leadership Plan* aims to transform the electricity generation from fossil fuel coal to a more sustainable low carbon energy source. Bioenergy is a low carbon renewable energy source that can contribute to the supply of more clean energy [2, 3]. So much as electricity transformed human well-being, it has also caused significant human health, ecosystem, and climate change damage [4–7]. Human health and ecosystems damage are external costs because the power plant does not take full account when deciding how to generate electricity [8, 9]. New investments on renewable energy sources are challenged by the province's deregulated electricity market system that does not appreciate the societal benefits of clean energy sources [10, 11]. Recognizing the societal external costs of energy production in energy planning could create a better playing field for low carbon electricity supply.

The Paris Agreement on climate change was ratified by the several nations to retain global warming below 1.5°C. This crucial agreement demonstrated that the world is committed to fight climate change. Pricing environmental externalities is a mechanism that supports the prospects for energy transition and transformation. For example, carbon pricing has been an effective way of promoting cleaner energy production for addressing global climate change in Quebec's transportation sector. By implementing a carbon price in its transportation system, the province of Quebec is able to reduce greenhouse gas (GHG) emissions and create economic revenues. To this effect, carbon credit auctions raised $1.2 billion, in which over $800 million of the money generated is used in the transportation sector.

The increased production of fossil fuels has increased Alberta's GHG emission by 47% since 1990 [12]. Alberta contributed 35.7% of the national total 700 $MtCO_2eq$ (million tons of carbon dioxide equivalent) GHG emissions in 2012. With only 11.2% of the total population, Alberta ranked second next to Saskatchewan in terms of emissions per capita, when compared to other provinces of Canada. Alberta introduced emission trading system and carbon taxes to reduce emissions from large GHG emitters in 2007. Large GHG emitters are required to reduce emissions by buying offsets, investing in technological innovations, or trading verified emission reduction from other cleaner industries. For example, the provincial government has mandated 2% biodiesel and 5% ethanol content in transportation fuels with 9 cent per liter tax exemption for biofuel producer [13]. However, current government policies do not encourage clean electricity and heat producers.

Electricity producers are less motivated to invest on renewables because environmental externalities do not appear in the electricity pricing system. Additionally, the negative impacts of environmental externalities are mare primarily born by society and not by producers. Accounting for environmental externalities is more effective than environmental regulation because it supports informed decision-making for meaningful climate change mitigation [14, 15]. The pool price of electricity from fossil fuel is higher than cleaner energy sources, when the economic value of environmental impacts resulting from air emissions is considered [16]. Previous studies on the externalities of electricity have largely focused on the damages caused by air pollution or global warming only [17, 18], and damage to ecosystems quality is ignored. Additionally, the assessment of environmental externalities at the power plant alone would underestimate the total economic impact [10, 19]. Studies have examined the implication of environmental externalities at power plant. However, the entire life cycle of the product must be examined for accurate societal life cycle cost (SLCC) damage by including the feedstock production and transport life cycle stages. On the other hand, previous studies focus mainly on solar and wind, whereas studies on the societal cost of bioenergy are limited [20]. Societal cost is usually quantified using specific models tailored for a specific product or jurisdiction. Few studies have applied the societal life cycle costing (LCC) method to determine the economic implication of environmental externalities in waste management [21]. The economic value of environmental externalities is traditionally estimated based on epidemiological studies, and the concept of life cycle costing has not been used to quantify externality. Rating the cost per the damage-adjusted life-years (DALY) of human health, and the potentially disappeared fraction of species on 1 $m^2$ of earth surface during 1 year (PDF.$m^2$.year) of ecosystems impact is controversial in the literature.

Incorporating the environmental externalities of products creates cost-effective and environmentally friendly solutions by promoting clean energy development [22, 23]. Alberta has implemented a carbon price in order to mitigate climate change [2]. However, the course of map for addressing the energy sustainability of the province has ignored bioenergy source. On the other hand, the externalities for ecosystem and human health damages must be also accounted into the pool price for most accurate total SLCC assessment. A societal life cycle costing method was applied to compare the economic value of environmental damages caused by coal fuel with bioenergy for the case of Alberta. In addition, the SLCC per kWh electricity generation was quantified in order to examine the retail costs of electricity.

## 2. Method

A societal LCC method was applied to investigate the policy-relevance of accounting environmental externalities. Societal LCC is a proven approach for measuring the cost–benefit of alternative investments due to the relatively larger set of costs included in the analysis. The most important aspect of the societal LCC lies the fact that the monetized environmental effects of societal costs are incorporated in the analysis [24, 25]. In such analyses, the economic and environmental impacts are integrated to compare alternative production systems. As a result, a societal LCC is a stand-alone method, and it is not followed by environmental or economic impacts results. This study used a model for environmental life cycle costing [26] to generate the economic impact of societal costs per kWh. The model developed in this study accounts the external cost for climate change, ecosystem, and human health damages. As such, the costs for climate change, human health, and ecosystems impacts were summed up with the environmental life cycle cost impact in order to yield a monetized total impact.

It is difficult to measure the costs for environmental externalities because they do not have a direct input/output counterpart like in the case of life cycle assessment (LCA) or life cycle costing (LCC) methods. Nevertheless, the monetary valuation of societal costs can be easily related to the notion of externalities in welfare economics. There are various approaches and methods of monetary valuation. The budget constraint method provides a better contribution for applications in LCA [27, 28]. In this study, the external cost of environmental impacts per unit of DALY and per unit of PDF.$m^2$.year was quantified based on the cost factors estimated by Weidema [27].

### 2.1. Electricity production scenario

The installed electricity generation capacity of Alberta is a mix of 40% of natural gas, 43% of coal, and 17% of combined renewable sources. Clean energy from hydrocarbon is the prime focus of Alberta's electricity strategy; however, the potential of bioenergy sources is ignored [29]. Therefore, the scope of this research was limited to understand the significance of bioenergy based on pellet in the transition and transformation of coal-fired electricity. Wood pellet feedstock was assumed for bioenergy production because it can be easily integrated into coal power plant technologies and infrastructure with minimal retrofitting. The prevailing scenario of coal-fired electricity was compared with three alternative bioenergy scenarios for a study period of 29 years, beginning from 2017 to 2046. This study period is in line with the lifetime for the best available power plant technology operating in Alberta.

#### *2.1.1. Electricity production reference scenario*

The reference scenario was modeled to represent business as usual of burning coal fuel for electricity supply. A sub-bituminous coal from High Vale mine area is direct-fired to produce electricity.

#### *2.1.2. Electricity production transformation scenario*

The transformation scenario, that is Scenario 2, represents a complete substitution of coal plants with 100% direct-mono-combustion of pellet biomass in existing coal power plant. This scenario ends the consumption of coal beginning from 2017.

#### *2.1.3. Transition scenario*

The *Climate Leadership Plan* of Alberta calls for electricity transition until 2030 and forces a complete transformation of coal power plants after 2030. Therefore, co-firing of coal with pellets until 2030 and the direct-firing of coal until 2030, both followed with pellet mono-combustion in the years 2031 through 2046 represented Scenario 3 and Scenario 4, respectively. Minor retrofitting of current power plants is required for co-firing of pellet with coal only [30, 31]. Direct co-firing with separate feed systems for pellet and coal was assumed for the analysis.

### 2.2. Data collection and handling

Primary data and Alberta specific settings were used to represent the environmental modeling of energy scenarios. The intermediate upstream and downstream unit processes of the life cycle were represented by generic data.

On the other hand, economic factors that are specific to Alberta's setting were used to model the life cycle cost (LCC) impact. Generic cost factors were considered for parameters that are similar across technologies.

### 2.3. System boundary

The system boundary and process flow diagram for energy pathways was drawn as shown in **Figure 1**. Biomass feedstock was assumed to be harvested from the *Division No. 13* and *Division No. 14 West* region of Alberta. Processes involved with biomass feedstock production are silviculture, felling, skidding, road construction, biomass preparation, and pelletization. The two recently commenced new coal plants in Alberta, *Genesee Thermal* and *Keephills*

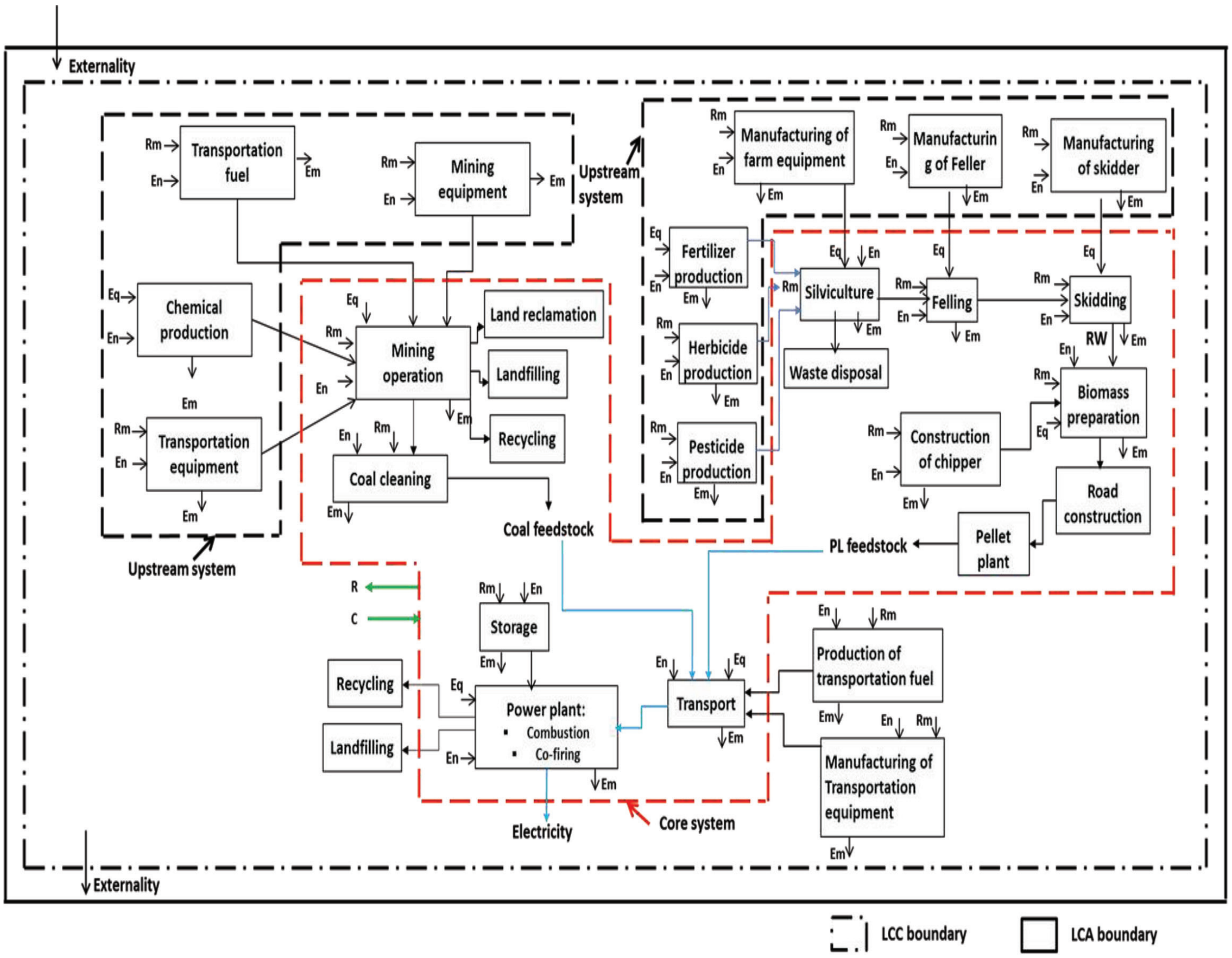


**Figure 1.** System boundary of energy pathways [26]. Note: R: Revenue; C: Cost; En: Energy; Rm: Raw material; Em: Emission; Eq: Equipment.

*Thermal*, electric power generating stations consume sub-bituminous coal from *Highvale mine*. The coal mine in *Highvale* operates a surface mining [32]. The basic processes for surface mining include mine fracturing, resizing the coal, coal preparation, and cleaning. Clean coal is hauled using trucks to the power plant for electricity generation [33].

The transportation subsystem accounted the transportation of chemicals, feedstock (coal or pellet), and other items between the boundaries of the forest field or coal mining, and the plant. Coal is combusted in a supercritical pulverized boiler to generate electricity. The inventory for the power plant subsystem begins at the plant gate of the power plant and ends with the production of electricity. *Genesee 3* is the first power plant in Canada to use supercritical pressure pulverized coal combustion technology [29]. Supercritical boilers operate at high temperature and pressure and employ a high-efficiency steam turbine. Coal and pellet are crushed, pulverized, and burned to create a high-pressure steam that turns a turbine shaft for electricity generation. The option for co-firing depends up on the co-firing level and the type of biomass feedstock. Direct co-firing is a proven combustion system for pulverizing pellet and coal feedstocks together. In this study, a heat rate of 20% pellet and 80% coal was considered for co-firing to produce 1 kWh of electricity. The power plant efficiency for supercritical pulverized boiler was estimated at 35.5% based on the annual electricity generation and coal consumption inventoried for the new power generation units in Alberta.

Pellet substitution and co-firing of pellet with coal require only minor retrofitting for integrating biomass to existing coal-fired power plants. Direct co-firing with separate feed systems for coal and pellet was considered for analysis. All of the life cycle activities from resource extraction and feedstock production, transportation, to the production of electricity, and any necessary waste disposal were considered. The environmental impact of electricity generation scenarios was quantified using a functional unit of 1 kWh for the case of Alberta. The IMPACTWorld+ impact assessment method was used to quantify the impacts on human health, ecosystem, and climate change.

The costs of electricity generation can be categorized into investment costs, operating costs, and externalities costs. LCC refers to all costs associated with the life cycle of the product system, including internalized cost of external effects, over a given study period [24, 25]. A LCC was conducted, with the same system specification as for LCA, to quantify the cost per functional unit of 1 kWh electricity generation [26]. The study period has been assumed to be 29 years based on the life-time for coal plants, as determined by the government of Alberta, and it begins at the same time with the base date. The study period of each system elapses from a base date or service period of 2017 through 2046.

The present-value method was used to quantify the economic impact of electricity production scenarios. Future costs were discounted from the end of the year they occur to the base date and summed up with the investment costs to give the total LCC. Only costs to be incurred on or after the base date were included in the base case. The constant dollar method was used in the study to estimate future money flows as it has the advantage of avoiding the need to project future rates of inflation or deflation. The value of dollar was fixed to 2016 US dollars as a reference to express all future amounts.

### 2.4. Calculation

#### *2.4.1. Cost of environmental externality*

Monetary valuation is used to determine the economic value of nonmarket goods. It can be applied in LCA, especially in the weighting phase, to compare the cost benefit between different impacts [28]. The willingness to pay by an individual for a small change in his/her quality of life (e.g. prolonging one's life by 1 year) can be valued monetarily [34, 35]. According to Weidema [27], the price rate for environmental damages ranged from $USD2.01 to $USD5.95 per pdf.m$^2$.year and $USD89399.73 to $USD135482.06 per DALY. In this study, the societal LCC of alternative electricity production scenarios was quantified by assuming an average rate of $USD4.0 per pdf.m$^2$.year and $USD 112440.9 per DALY.

The external cost of electricity generation was calculated using Eqs. 1 and 2.

$$Externality\ of\ Health(\$/kWh) = (Health\ impact\ (DALY))/(Functional\ unit\ (kWh)) * Price\ rate\ for\ Health(\$/DALY) \quad (1)$$

$$Externality\ of\ Ecosystem(\$/kWh) = \left(Ecosystem\ impact\ (pdf.m2.year)\right)/(Functional\ unit\ (kWh)\ ) * Price\ rate\ for\ Ecosystem\left(\$/(pdf.m2.year)\right) \quad (2)$$

*2.4.2. Societal LCC of energy scenario*

The environmental life cycle cost impact and the monetized value of externalities are summed up to produce the societal life cycle cost of electricity production scenario. The fraction of human health and ecosystem impacts caused due to global warming per functional unit of 1 kWh electricity was subtracted from the total environmental damage in order to avoid the double counting of externality due to climate change. The environmental life cycle cost analysis considered a discount rate of 0.1% [26]. The societal LCC was calculated using Eq. (3).

$$\text{Societal LCC (\$/kWh)} = \text{Environmental LCC (\$/kWh)} + \text{Externality (\$/kWh)} \quad (3)$$

where the environmental LCC figures were drawn from a previous research which applied the same system boundary [26].

*2.4.3. Economic benefit of energy transition and transformation scenarios*

Economic benefit is achieved by saving a sum of money through averting the conventional scenario of coal-fired electricity using a more clean electricity production scenario. Eq. 4 was applied to quantify the benefit of Alberta's electricity grid transformation and transition scenarios.

$$\text{Benefit of scenario (\$/kWh)} = \text{SLCC of scenario 1 (\$/kWh)} - \text{SLCC of alternative scenario (\$/kWh)} \quad (4)$$

## 3. Results and discussion

### 3.1. Economic value of externalities

The economic value of an environmental externality was quantified by multiplying the environmental impact per functional unit of 1 kWh electricity with the respective price rate. As shown in **Table 1**, coal-fire electricity scenario has the highest economic value of environmental externalities. For all energy scenarios, the economic value of damage to ecosystem was 559–634% higher than the economic value of damage to human health. The transformation scenario of pellet mono-combustion demonstrated the lowest economic value for all environmental damages.

As shown in **Figure 2**, Scenario 1 exhibited the highest social cost when compared to alternative wood-biomass based electricity generation scenarios. The external cost of Scenario 2 is only 9.5% of the external cost of Scenario 1. On the other hand, Scenario 3 and 4 demonstrated 44–53% of the external cost of Scenario 1.

| Environmental damage | LC environmental impact/kWh | | | | Price rate, $ | Economic value, C/kWh | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Coal mono-combustion | Pellet mono-combustion | Coal & pellet mono-combustion | Co-firing & pellet mono-combustion | | Coal mono-combustion | Pellet mono-combustion | Coal & pellet mono-combustion | Co-firing & pellet mono-combustion |
| Human health, DALY | 4.55E-06 | 4.76E-07 | 2.44E-06 | 2.04E-06 | 112440.9 | 51.19 | 5.35 | 27.45 | 22.98 |
| Ecosystem, PDF.m2.yr | 0.939 | 0.088 | 0.499 | 0.417 | 4.0 | 375.77 | 35.29 | 199.53 | 166.70 |

**Table 1.** Economic value of environmental impact (¢: Cent).

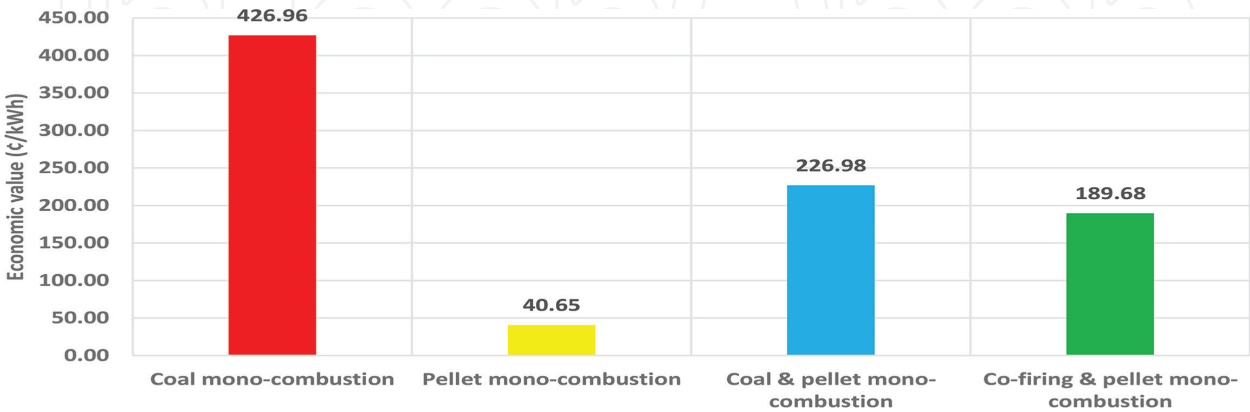


**Figure 2.** Social cost of electricity generation.

### 3.2. Societal LCC of electricity

The societal LCC of electricity is a sum of the environmental externality cost and the economic impact (i.e., environmental LCC). Coal power plants caused the highest environmental externality of electricity generation (**Table 2**). On the other hand, the transition scenarios caused higher economic impact (i.e., environmental LCC), but resulted in lower environmental externality, when compared to coal-fired electricity generation. As shown in **Table 2**, coal-fired electricity caused the highest SLCC, when compared to alternative electricity production systems. Although coal fuel combustion is the most cost effective scenario, its SLCC was nearly 10 times higher than electricity transformation scenario based on biomass pellet. Therefore, transitioning and transforming the coal power plants in Alberta with bioenergy systems has greater economic benefit. As a result, decarbonizing of Alberta's electricity grid to phase out the coal plants would significantly reduce the SLCC. Transitioning of the coal plants in Alberta also would result in lower aggregated cost.

The average price for electricity observed maximum values ranging from 10.8 to 14.05 ¢/kWh and minimum values ranging from 2.4 to 3.4 ¢/kWh [36]. As per to *Alberta Utilities Commission*, the generation of electricity covers nearly 50% of the total pool price for electricity. Thus, the societal life cycle cost of Scenario 1 amounted 7908–25,121% higher than the cost of electricity generation, and at times higher.

There is always uncertainty on the results for SLCC analysis because there is no one way of modeling a reality. Subjective choices made related to willingness to pay can influence the study results. Therefore, a sensitivity analysis was carried out to see the influence of the societal price rate assumed for environmental damage on the SLCC results (**Table 3**). The

| Cost factor | Unit | Coal mono-combustion | Pellet mono-combustion | Coal & pellet mono-combustion | Co-firing & pellet mono-combustion |
|---|---|---|---|---|---|
| Environmental LCC | ¢/kWh | 0.1 | 0.94 | 1.19 | 4.45 |
| Environmental externality | ¢/kWh | 426.96 | 40.65 | 226.98 | 189.69 |
| Societal LCC | ¢/kWh | 427.06 | 41.59 | 228.17 | 194.13 |

**Table 2.** Societal life cycle cost per kWh.

| Cost factor | Unit | Coal mono-combustion | Pellet mono-combustion | Coal & pellet mono-combustion | Co-firing & pellet mono-combustion |
|---|---|---|---|---|---|
| Environmental LCC | ¢/kWh | 0.1 | 0.94 | 1.19 | 4.45 |
| Environmental externality | ¢/kWh | 213.48 | 20.32 | 113.49 | 94.84 |
| Societal LCC | ¢/kWh | 213.58 | 21.26 | 114.68 | 99.29 |

**Table 3.** Sensitivity analysis: variation of SLCC cost per kWh for 50% increase in social cost of environmental externality.

sensitivity analysis demonstrated that a 50% decrease of price rates per DALY and PDF would not change the overall outcome.

### 3.3. Economic benefit of electricity transformation

The energy balance of each scenario was analyzed based on the near term electricity generation outlook by AESO (*Alberta Electricity Systems Operator*) [29]. AESO has taken into account several factors, including technology development; environmental goals; availability of resources; and investment finance in forecasting future electricity production. According to this outlook, the coal-fired electricity installed capacity is expected to decrease from 5900 MW in 2017 to 2876 MW in 2032 [29]. To fit the purpose of Alberta's *Climate Leadership Plan*, we assumed that the province's installed capacity would achieve 2876 MW in 2030 (**Figure 3**).

The annual potential of sustainably available forest wood biomass supply for energy in Alberta is estimated at 165.04 PJ [13]. The amount of wood pellet delivered at the power plant was estimated to be 149 PJ, by assuming a 10% of haul loss during feedstock transportation.

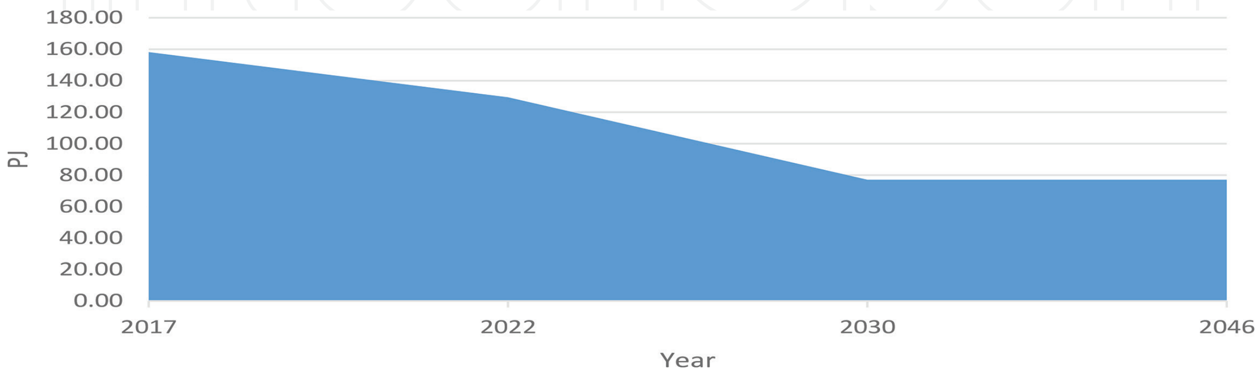


**Figure 3.** Projection of electricity generation from coal fuel.

Considering a power plant efficiency of 33.73%, the energy content of pellet would yield approximately 50.1 PJ of electricity. To phase-out the coal-fired electricity, this same amount of pellet feedstock was fed annually to the power plant. The coal power plants in Alberta have a capacity factor of 85%. Consequently, pellet alone cannot completely transform the current coal-fired installed capacity before the year 2046 (**Figure 4**). It is worth noting that the difference amount of electricity capacity will be addressed by other renewables.

A total of 13,916.67 GWh per year was considered for energy balance analysis. This implies that approximately 403,583.3 GWh (or 1452.9PJ) of electricity is produced during the projected 29 years study period. Given $4.27 per kWh for the societal life cycle cost of electricity generation from coal fuel, coal power plants are costing on average 130.5 billion USD per year. As shown in **Table 4**, ending electricity from coal with wood pellet can save 53.7 billion USD per year. Therefore, the societal life cycle cost per year of coal power plants in Alberta represents 15.8% of the province's GDP and 343.7% of the total expenditure on health. To this effect, bioenergy has the potential to finance Albert's expenditure on health with a huge surplus going for technology development or other clean energy incentives. Therefore, the transformative potential presented by carbon pricing toward a cleaner future is limited.

Canada's total expenditure on health per capita was $4641.0 in 2014, which is equivalent to 10.4% of its gross domestic product (GDP) [37]. In contrast, Alberta's total expenditure on health care was nearly $17,291.8 million, and a total GDP of $375,756 in 2014 [38, 39]. For a population of 4,120,900 the total expenditure per capita and total expenditure on health as percentage of GDP was estimated to be $4196.1 and 4.6% respectively [40]. This demonstrates that Alberta has lower expenditure per capita as compared to the national average

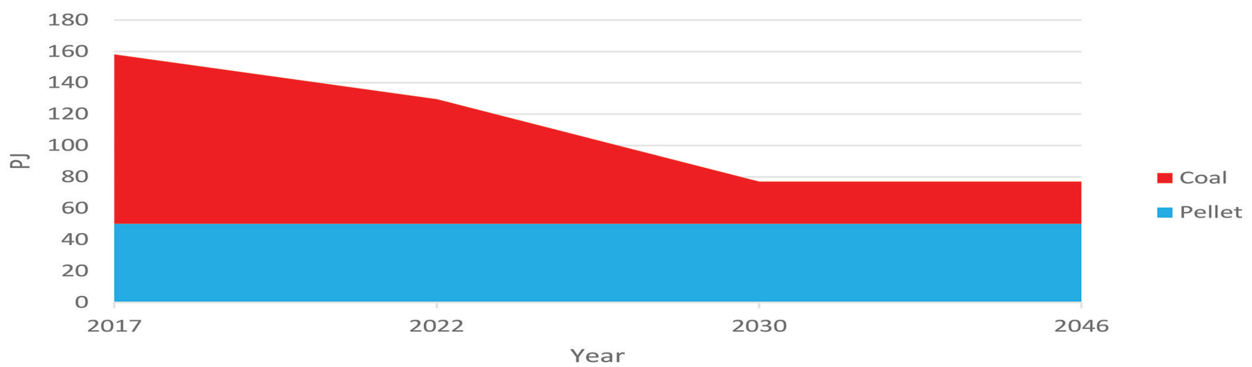


**Figure 4.** Projection of annual electricity generation for the transformation scenario.

| Fuel for electricity generation | Electricity generation per year, GWh | SLCC, $/kWh | Total SLCC, $ |
|---|---|---|---|
| Coal fuel | 13,916.67 | 4.2706 | 123,549,452,494.59 |
| wood biomass pellet | 13,916.67 | 0.4159 | 12,493,981,020.00 |
| Economic benefit of transformation | | | 53,645,153,677.40 |

**Table 4.** Economic benefit of transformation based on pellet.

expenditure. This implies that the annual SLCC of coal combustion in Alberta represents 15.82% of its GDP and 343.7% of the total expenditure on health care. Transforming coal plants with pellet can significantly reduce the annual expenditure on health care by 310.2%.

### 3.4. Transformative potential of carbon price

This study examines the transformative potential of carbon price, which used to be determined by a political will, instead of based on market willingness to pay monetary valuation method. The rate for social cost of environmental damages is usually determined from either epidemiological (or clinical) studies or based on willingness to pay approaches. The Government of Alberta has put a carbon price rate of USD $11.43 per ton of $CO_2$ emission. This carbon tax rate was used to estimate the external cost of human health damage per unit of DALY, and the ecosystems damage per unit of PDF.m$^2$.year. Thus, the economic value per unit of DALY was estimated based on the cost factor for $CO_2$ equivalent. This study is its first of kind to generate cost rate for DALY and pdf.m2.year based on a specified carbon tax rate.

The *IMPACTWorld + endpoint* LCA method at *characterization level* quantifies the environmental impact per functional unit of 1 kWh electricity generation in units of DALY for short-term and long-term impacts on human health, and PDF.m$^2$.year for short-term and long-term impacts on ecosystem. Similarly, the *IMPACTWorld + endpoint* method at *damage level* quantifies the environmental damage per functional unit of 1 kWh electricity generation in units of DALY for human health and PDF.m$^2$.year for ecosystem. On the other hand, the *weighting step* in a LCA method quantifies all environmental impact indicators in the same unit of *Yen2000* (i.e., the value of Yen currency as adjusted to its value in year 2000). All these results can be exported in to an Excel directly from the SimaPro software that was used to model the LCA. The environmental impact results for climate change can be obtained alternatively in units of carbon dioxide equivalent ($CO_2$ eq), PDF.m$^2$.year, and DALY from the programing software. Therefore, the unit of $CO_2$ eq impact for climate change at midpoint can be related to the DALY and PDF.m$^2$.year environmental damages at endpoint. Thus, the ratio of DALY to PDF.m$^2$.year was estimated to be 1 DALY for 528870.3 PDF.m$^2$.year by combining the values for damage assessment and the weighting steps in LCA. These values were further related to the impact values at midpoint to estimate the factors for DALY and PDF.m$^2$.year, as compared to 1 ton of $CO_2$ equivalent. Given the rate for carbon price $11.43 per ton of $CO_2$ eq, the price rate for human health and ecosystem damages were estimated to be $2236.8 per DALY and $0.00423 per pdf.m$^2$.year, respectively. The monetary valuation given in Section 2.4.1. earlier is 50 times greater than the cost rate per DALY, and 945 times greater than the cost per pdf.m2.year, respectively. This implies that the rate assigned politically for carbon tax underestimates the actual valuation to environmental damage.

## 4. Conclusion and policy implications

The costs of environmental externalities are not considered during planning nor are they accounted in the retail price of electricity. This research applied a novel societal life cycle costing approach to estimate the economic values of environmental damages to society that result from coal and biomass fired electricity generation. Coal-fired electricity has the highest economic value of environmental externalities, whereas pellet mono-combustion demonstrated the lowest economic value for all environmental damages. On the other hand, the transition scenarios caused higher economic impact, but resulted in lower environmental externality, when compared to coal-fired electricity generation. Although coal fuel is cheaper to produce electricity, yet its societal LCC is significantly higher than bioenergy systems. Subjective choices made related to willingness to pay can influence the study results. A sensitivity analysis demonstrated that a 50% decrease of price rates per DALY and PDF would not change the overall outcome. Therefore, bioenergy can potentially support in decarbonizing the electricity grid toward a more sustainable system. Mainstreaming of environmental externalities creates market advantages for low carbon energy sources. Coal power plants cause Alberta to lose at least $117.8 billion per annum due to externalities. Ending electricity from coal with wood pellet can save 53.7 billion USD per year. The societal life cycle cost per year of coal power plants in Alberta represents 15.8% of the province's GDP and 343.7% of the total expenditure on health. Carbon pricing alone cannot meaningfully support the prospect for energy transformation. Externalities for health and ecosystems should also be priced and included in the electricity market.

## Author details

Yemane W. Weldu[1,2]*

*Address all correspondence to: ywweldem@ucalgary.ca

1 Division of Sustainability, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar

2 Faculty of Environmental Design, University of Calgary, Calgary, Alberta, Canada

## References

[1] A. Energy, Electricity System Improvements, 2015 (2016). http://www.energy.alberta.ca/index.asp

[2] Weldu YW, Assefa G. Evaluating the environmental sustainability of biomass-based energy strategy: Using an impact matrix framework. Environmental Impact Assessment Review. 2016;**60**:75-82. DOI: 10.1016/j.eiar.2016.05.005

[3] Weldu YW. Life cycle human health and ecosystem quality implication of biomass-based strategies to climate change mitigation. Renewable Energy. 2017;**108**:11-18. DOI: 10.1016/j.renene.2017.02.046

[4] J. Deyette, B. Freese, Burning Coal, Burning Cash: Ranking the States that Import the Most Coal, Union of Concerned Scientists, 2010

[5] Lockwood AH, Welker-Hood K, Rauch M, Gottlieb B. Coal's assault on Human Health. Physicians for Social Responsibility Report; 2009

[6] Weldu YW, Assefa G. Life Cycle Human Toxicity and Ecotoxicity Assessment of Bioenergy Strategy in Decarbonizing Alberta's Grid. In: LCA XV, American Center for Life Cycle Assessment, The University of British Columbia, Vancouver, Canada; 2015

[7] Weldu YW, Assefa G, Jolliet O. Life cycle human health and ecotoxicological impacts assessment of electricity production from wood biomass compared to coal fuel. Applied Energy. 2017;**187**:564-574. DOI: 10.1016/j.apenergy.2016.11.101

[8] Schneider CG, Banks JM, Tatsutani M. The Toll from Coal: An Updated Assessment of Death and Disease from America's Dirtiest Energy Source. Clean Air Task Force. 2010

[9] Krewitt W, Heck T, Trukenmüller A, Friedrich R. Environmental damage costs from fossil electricity generation in Germany and Europe. Energy Policy. 1999;**27**:173-183

[10] Anderson K. A Costly Diagnosis: Subsidizing Coal Power with Albertan's Health. Pembina Institute for Appropriate Development; 2013

[11] Weldu YW. Accounting for Human Health and Ecosystems Quality in Developing Sustainable Energy Products: The Implications of Wood Biomass-based Electricity Strategies to Climate Change Mitigation. Canada: University of Calgary; 2017. DOI: 10.5072/PRISM/24649

[12] E. Canada. National Inventory Report 1990-2012: Greenhouse Gas Sources and Sinks in Canada; 2013. http://www.ec.gc.ca/ges-ghg/

[13] Weldemichael Y, Assefa G. Assessing the energy production and GHG (greenhouse gas) emissions mitigation potential of biomass resources for Alberta. Journal of Cleaner Production. 2016;**112**:4257-4264. DOI: 10.1016/j.jclepro.2015.08.118

[14] Spalding-Fecher R, Matibe DK. Electricity and externalities in South Africa. Energy Policy. 2003;**31**:721-734

[15] Prakash R, Bhat IK. Energy, economics and environmental impacts of renewable energy systems. Renewable and Sustainable Energy Reviews. 2009;**13**:2716-2721

[16] Klaassen G, Riahi K. Internalizing externalities of electricity generation: An analysis with MESSAGE-MACRO. Energy Policy. 2007;**35**:815-827

[17] Machol B, Rizk S. Economic value of US fossil fuel electricity health impacts. Environment International. 2013;**52**:75-80

[18] Markandya A, Wilkinson P. Electricity generation and health. Lancet. 2007;**370**:979-990

[19] Hainoun A, Almoustafa A, Aldin MS. Estimating the health damage costs of Syrian electricity generation system using impact pathway approach. Energy. 2010;**35**:628-638

[20] Owen AD. Renewable energy: Externality costs as market barriers. Energy Policy. 2006; **34**:632-642

[21] Martinez-Sanchez V, Tonini D, Møller F, Astrup TF. Life-cycle costing of food waste management in Denmark: Importance of indirect effects. Environmental Science & Technology. 2016;**50**:4513-4523

[22] Munksgaard J, Ramskov J. Effects of internalising external production costs in a north European power market. Energy Policy. 2002;**30**:501-510

[23] Owen AD. Environmental externalities, market distortions and the economics of renewable energy technologies. The Energy Journal. 2004:127-156

[24] Swarr TE, Hunkeler D, Klöpffer W, Pesonen H-L, Ciroth A, Brent AC, Pagan R. Environmental life-cycle costing: A code of practice. International Journal of Life Cycle Assessment. 2011;**16**:389-391

[25] Hunkeler D, Lichtenvort K, Rebitzer G. Environmental Life Cycle Costing. Pensacola Florida, USA: CRC Press; 2008

[26] Weldu YW, Assefa G. The search for most cost-effective way of achieving environmental sustainability status in electricity generation: Environmental life cycle cost analysis of energy scenarios. Journal of Cleaner Production. 2017;**142**:2296-2304. DOI: 10.1016/j.jclepro.2016.11.047

[27] Weidema BP. Using the budget constraint to monetarise impact assessment results. Ecological Economics. 2009;**68**:1591-1598

[28] Pizzol M, Weidema B, Brandão M, Osset P. Monetary valuation in life cycle assessment: A review. Journal of Cleaner Production. 2015;**86**:170-179. DOI: 10.1016/j.jclepro.2014.08.007

[29] AESO. AESO 2012 Long-term Outlook, 2015; 2012. http://www.aeso.ca/index.html

[30] Sebastián F, Royo J, Serra L, Gómez M. Life cycle assessment of greenhouse gas emissions from biomass electricity generation: Cofiring and biomass monocombustion. In: Proceedings of the 4th Dubrovnik Conf. Sustain. Dev. Energy Water Environ. Syst. Dubrovnik, Croatia. 2007. pp. 4-8

[31] Shao Y, Wang J, Preto F, Zhu J, Xu C. Ash deposition in biomass combustion or co-firing for power/heat generation. Energies. 2012;**5**:5171-5189

[32] Meldrum J, Nettles-Anderson S, Heath G, Macknick J. Life cycle water use for electricity generation: A review and harmonization of literature estimates. Environmental Research Letters. 2013;**8**:15031

[33] C. Power, Capital Power Corporation's Genesee Generating Station, Canada: Capital power; 2015 (2012)

[34] Zhang J, Smith KR, Ma Y, Ye S, Jiang F, Qi W, Liu P, Khalil MAK, Rasmussen RA, Thorneloe SA. Greenhouse gases and other airborne pollutants from household stoves in China: A database for emission factors. Atmospheric Environment. 2000;**34**:4537-4549

[35] Desaigues B, Ami D, Bartczak A, Braun-Kohlová M, Chilton S, Czajkowski M, Farreras V, Hunt A, Hutchison M, Jeanrenaud C, Kaderjak P, MácA V, Markiewicz O, Markowska A, Metcalf H, Navrud S, Nielsen JS, Ortiz R, Pellegrini S, Rabl A, Riera R, Scasny M, Stoeckel ME, Szántó R, Urban J. Economic valuation of air pollution mortality: A 9-country contingent valuation survey of value of a life year (VOLY). Ecological Indicators. 2011;**11**:902-910

[36] AESO. How Have Electricity Prices in Alberta Evolved over Time? 2016. http://www.aeso.ca/index.html

[37] WHO, Health statistics and information systems, 2016 (2015). http://www.who.int/countries/can/en/

[38] S. Canada. Gross domestic product, expenditure-based, by province and territory, CANSIM, Table 384-0038. 2016; 2015. http://cansim2.statcan.gc.ca/

[39] S. Canada. Health and social service institutions revenue and expenditures, by province and territory, CANSIM, Table 385-0008. 2016; 2010. http://cansim2.statcan.gc.ca/

[40] S. Canada. Population by year, by province and territory, CANSIM, Table 051-0001. 2016; 2015. http://cansim2.statcan.gc.ca/

IntechOpen