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Sustainability of an energy conversion system in Canada involving large-scale integrated hydrogen production using solid fuels

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Abstract
The sustainability of a large-scale hydrogen production system is assessed qualitatively. The system uses solid fuels and aims to increase the sustainability of the energy system in Canada through the use of alternative energy forms. The system involves significant technology integration, with various energy conversion processes (e.g., gasification, chemical looping combustion, anaerobic digestion, combustion power cycles-electrolysis and solar-thermal convertors) interconnected to increase the utilization of solid fuels as much as feasible in a sustainable manner within cost, environmental and other constraints. The qualitative analysis involves ten different indicators for each of the three dimensions of sustainability: ecology, sociology and technology, applied to each process in the system and assessed based on a ten-point quality scale. The results indicate that biomasses have better sustainability than coals while newer secondary processes are essential for primary conversion to be sustainable, especially when using coals. Also, new developments in CO_2 use (for algae-to-oil and commercial applications) and storage will in time help improve sustainability.

Keywords: Centralized hydrogen production, Hydrogen energy, Solid fuels, Coal, Biomass, Municipal solid waste, Gasification, Anaerobic digestion, Sustainability, Canada energy market.

1. Introduction

Technologies to convert carbon-based solid fuels to useful energy forms are available, although some challenges remain regarding pollution capture. These technologies include advanced gasification, combustion and gas-solid looping processes. Some are at the developmental stage while others are commercially available [1-3]. Single-function systems (i.e. a system with only one product, like electricity or a fuel or a chemical commodity) predominate in the existing Canadian energy market [4]. A polygeneration system involves a mix of electricity, chemical commodity, fuel and heat production within a single plant. In recent years, the integration of various energy conversion technologies and processes so as to form polygeneration systems has received increasing attention from the Canadian industry and government [5].

Current scientific data on global warming [6] have added momentum to the initiatives being considered by governments and industries to switch to non-carbon-based energy sources. For example, many propose for a hydrogen energy system in which hydrogen and electricity are the primary energy carriers, facilitating the use of non-fossil-based energy resources [3,7]. Many feel that the shift to alternative energy sources would also help to improve national economies by creating new industries and employment opportunities, advance policies to facilitate new investments and business models and create funds for development through large government stimulus packages [7-9]. The most advantageous alternative energy carrier is often predicted to be hydrogen, along with hydrogen-based fuels. Hydrogen energy could find significant applications in the transportation sector and distributed power generation, and would further facilitate renewable energy implementation by acting as a storage medium [10,11]. Many countries including Canada have already initiated research and commercial programs to produce alternative fuels such as ethanol and hydrogen [3,7,10,12,13].

Hydrogen energy systems could also lead to an increase in the contribution of coal and natural gas to local energy markets, where they are mainly used for heating and power generation. When using hydrogen produced from coal or natural gas in vehicles, the CO_2 emissions can be addressed at the source (the hydrogen production process) before the energy carrier is delivered to the vehicles, making the capture and storage of CO_2 more economic [3]. Such a centralized ability to capture carbon dioxide is not possible when using gasoline or ethanol or Fischer-Tropsch-derived diesel fuel. The post-combustion capture of CO_2 from coal and natural gas in power plants is less economic than CO_2 capture associated with hydrogen production when using these two energy sources [14], except when using oxy-fuel combustion [15], which is currently at the developmental stage.

The need for large-scale hydrogen production, especially in countries with large transportation sectors, has been suggested in numerous hydrogen initiatives [3,7,10,12,13,16]. In line with this need, an integrated approach to large-scale hydrogen production using solid fuels is proposed here, which aims to improve the sustainability of the energy system. The conceptual design for this approach is shown in Figure 1. This approach involves a synthesis of multi-conversion sub-systems into a large single-function system to produce hydrogen. Various solid fuels are used, including coal, biomass, municipal solid wastes (MSWs), forestry-based solid wastes, energy crops, and agricultural and industrial solid residue. These solid fuels provide the thermo-chemical energy required for several different primary conversion processes (sub-systems) working together in one location, resulting in the simultaneous production of several hydrogen streams (as shown in Figure 1). The hydrogen is derived in various stages from the hydrogen portion of hydrocarbons and by splitting water.

The type of large-scale integration proposed here would create opportunities to enhance the utilization of solid fuels by reducing overall material and energy waste [2], thereby reducing environmental pollution while meeting proposed greenhouse gas limits in Canada [15]. These limits may be achieved in part by replacing gasoline with non-carbon-based transportation fuels such as hydrogen or electricity. The transportation sector is significant in Canada since it contributes 30% more CO_2 than the power generation sector [17]. A sustainability assessment of such a large-scale system in a fast changing Canadian energy market is necessary to help in decision making, along with techno-economic assessments of each component and sub-system within the proposed system, to identify the best combination of components.

Measuring sustainability is a major issue as well as a driving force in determining the impact of various indicators on each of the components within an advanced energy system [18]. An effective sustainability indicator has to meet characteristics reflecting a problem and criteria to be considered [19]. Selection, grouping, judging, weighing and normalizing of these indicators are somewhat subjective and dependent on the domain for the sustainability analysis (the system shown in Figure 1 in this work) [18,20,21]. A qualitative analysis on the system in Figure 1 is undertaken here, involving ten different indicators for each of the three dimensions of sustainability: (i) ecology, (ii) sociology and (iii) technology. These indicators are applied to each process in the system and assessed based on a ten point scale. Each process or element is selected for the system, based on a near-average sustainability value for at least one of the dimensions. Rather than estimating a hydrogen energy-based sustainability ratio [22], a content-oriented quality grade is assigned to the ten indicators in each of the three dimensions for each process or element involved in the proposed system.

The current work follows the work of Gnanapragasam et al. [23], where the large-scale system (Figure 1) was proposed and its feasibility investigated within current and foreseeable Canadian energy markets. The objective in this work is to perform a qualitative sustainability assessment of such a system in Canada. The steps in the analysis include the following:

- Definition of qualitative sustainability indicators, ten for each of the three dimensions, for every process or element involved in the proposed system.

- Generation of values for each these indicators using a ten point grade based on a high of 1 and low of 0 as indices, depending on the characteristic of the problem or criteria associated with each element or process.
- Assessment (separately and jointly) of the generated indices for the six categories of elements or processes.
- Comparison of the indicators within each sustainability dimension, to highlight the processes requiring attention for improving sustainability, by categorizing the components of the system into six groups: (i) solid fuels; (ii) on-site fuel handling; (iii) primary conversion processes; (iv) secondary conversion processes; (v) carbon capture and sequestration (CCS); and (vi) future extensions.

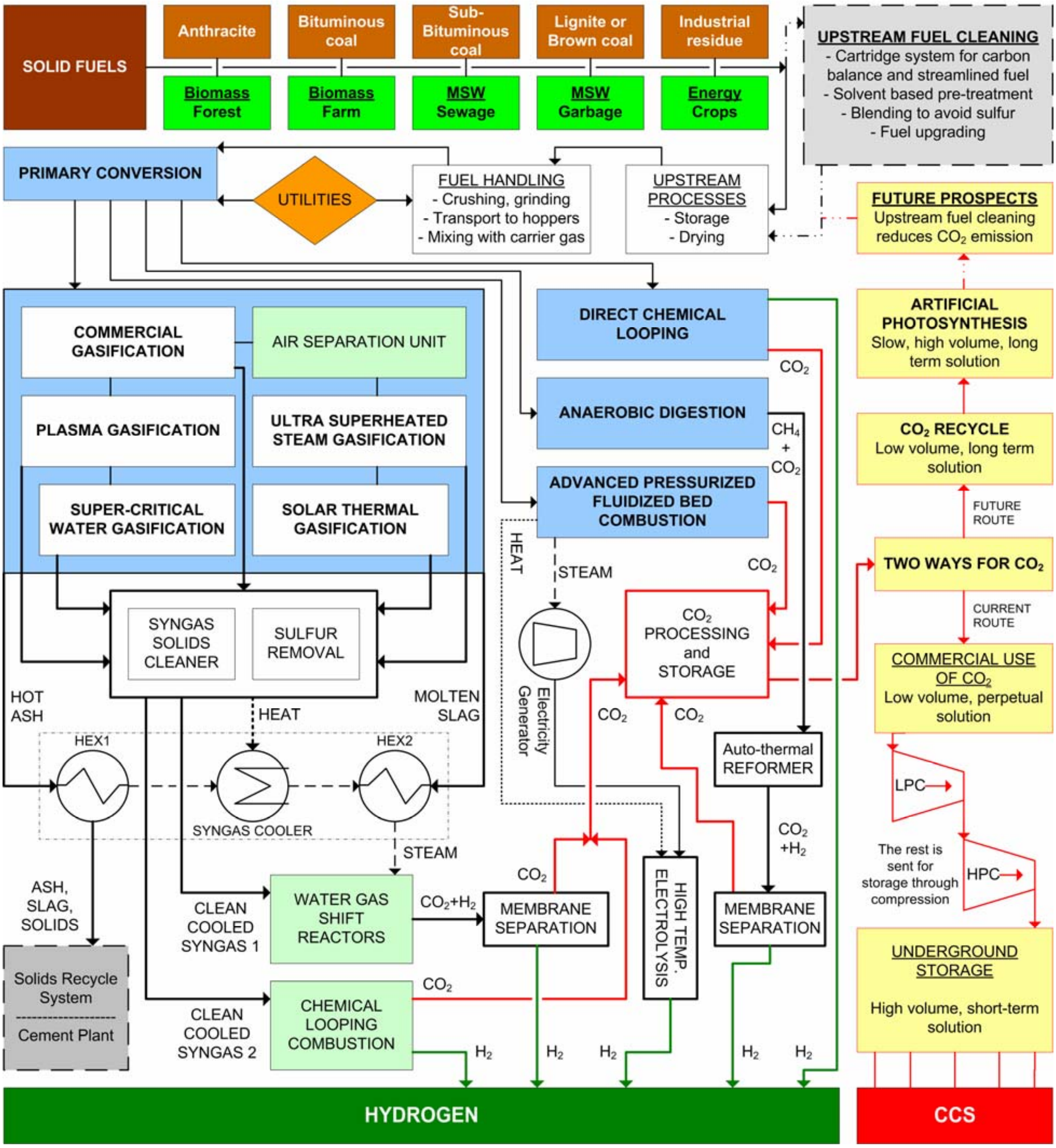

Figure 1. Simplified concept for a large-scale, integrated hydrogen production system using solid fuels: adapted from Gnanapragasam et al., 2010 [60]

It is assumed that energy system changes will occur based on past trends from other projects within Canada's energy market. It is recognized that enhanced sustainability of such a large system depends on the choice of technologies, which in turn is dependent on future changes in the global energy market.

2. Large-scale integrated hydrogen production system

The large-scale production of hydrogen using an integration of conversion technologies as shown in Figure 1 is intended to exploit the advantages of each individual technology developed to use certain types of solid fuels. The proposed system is described here by following the flow of materials starting from solid fuels (top left-hand corner in Figure 1). The upstream processes address the steady supply of solid fuels by storing and drying in large quantities, which is common to coals and biomass, with commercially established methods [24]. The required utilities include air, water/steam and electricity for various processes and equipment in the system. The primary energy conversion processes include gasification, direct chemical looping, anaerobic digestion and combustion. Except for combustion, these processes involve conversion of solids into gases containing varying proportions of hydrogen.

2.1 Gasification processes

Solid gasification is an established and tested commercial process for converting solid fuels into a gaseous form (syngas), from which hydrogen can be enriched and separated with further processing (secondary energy conversion stages).

The gasification process in general comprises the following devices: fuel delivery system, air separation unit, ash collecting hoppers, syngas cooler and jacket steam generator [24]. Gasification is considered an effective method for thermal hydrogen production [25] and is expected to play an important role in the transition to a hydrogen economy [26]. A comparison of commercial gasification processes [27] indicated that the transport gasifier has the lowest cost for electricity generation, while the Texaco and British Gas Lurgi gasifiers have the highest electricity costs.

The plasma gasification in Figure 1 is a different type of gasification process, which can be used for producing hydrogen-rich syngas with no limitation on the feedstock characteristics, and which requires only a limited amount of air/oxygen [28]. Plasma gasification is a high-temperature pyrloysis process that is becoming commercially popular in solid waste management facilities. This process can produce 30% (by volume) more syngas when steam is used as the gasifying medium. Plasma gasification is more suitable for sewage sludge and solid fuels with higher moisture contents [29,30].

Ultra-superheated steam (USS) gasification yields ultra-superheated steam composed of substantial amounts of water vapour, carbon dioxide and highly reactive free radicals at temperatures ranging from 1316 to 2760^{o}C [31]. When this clear colourless flow comes into contact with solid fuels, it induces rapid gasification to form a syngas with 50% more hydrogen content than other gasification processes [32]. This process offers better use of low-quality steam by using methane to produce the USS.

The supercritical water gasification (SCWG) process [33] exploits the physical and chemical properties of water above its critical point (T = 374^{o}C, P = 221 bar). These properties allow a nearly complete conversion of the organic substances contained in solid fuels into an energy-rich syngas containing hydrogen, carbon dioxide and methane. The break-even point between thermal gasification and supercritical water gasification is approximately 40% moisture content [34].

Solar gasification is a hybrid of solar and fossil-fuel based endothermic processes, in which fossil fuels are used exclusively as the chemical source for hydrogen production, and concentrated solar radiation as the source of high-temperature process heat [35]. Methods for carrying out high-temperature reactions such as biomass pyrolysis or gasification using solar energy have been reported [36], and they have been coupled with chemical looping combustion for hydrogen production. Solar thermal gasification of corn stover [37] showed that it has higher solid-to-gas conversion efficiencies than alternative processes.

More details on these processes are included in a review [38] of primary energy conversion technologies for producing hydrogen from solid fuels.

2.2 Direct chemical looping combustion

Chemical looping combustion (CLC), developed in the mid 1990s [39], uses metallic oxide as an oxygen carrier for the combustion process. During the reaction in the reduction reactor, the oxygen in the metal oxide is exchanged with the carbon in the fuel, forming CO_2 and water [40-42]. The water is condensed to separate CO_2, which is stored. Hydrogen is produced from water in the oxidation reactor where the metal is converted back to its oxide. This process has a greater potential for CO_2 separation compared to membrane separation of CO_2. There are two options for using chemical looping combustion during the reduction and oxidation processes to produce two streams (hydrogen and CO_2). The first option is after gasification by using syngas to reduce the metal oxides and the second is by using solid fuels directly with metal oxides [42-44].

2.3 Anaerobic digestion

Anaerobic digestion is a biological process in which organic wastes are converted in the absence of air to biogas, i.e. a mixture of methane (55-75 vol. %) and carbon dioxide (25-45 vol. %) as well as small amounts of hydrogen sulphide (H_2S) and ammonia (NH_3). During anaerobic digestion, typically 30-60% of the solid input is converted to biogas [45]. The by-products consist of an undigested residue and various water-soluble substances. Depending on the digestion system (wet or dry), the average residence time is between ten days and four weeks. The use of biomass and organic waste streams via anaerobic digestion has the potential to play a key role in fostering energy recovery from biodegradable waste in a sustainable manner [46]. With current developments in reformer technologies, hydrogen can be produced from methane derived from anaerobic digestion of organic waste material, much of which is currently land filled [47].

2.4 Advanced pressurized fluidized bed combustion

Pressurized fluidized bed combustion (PFBC) of solid fuels to produce electricity [48] uses a combination of Brayton and Rankine power cycles. In the proposed system, electricity generated by PFBC is used for several utilities within the system and the remainder is used to split water into hydrogen and oxygen in an high temperature electrolyser [48,49]. The heat for the electrolyser is derived from the PFBC. PFBC can also be coupled with a gasification process by having only part of the solid fuel gasified (partial gasification) for hydrogen production and combusting the char remaining from the partial gasification step in the PFBC unit to produce steam for electricity generation [14]. This is one of the reasons for opting to use PFBC in the proposed system, which is in addition to it being one of the most efficient combustion processes for solid fuels, along with ultra-super critical pulverized coal combustion [2,14,50].

2.5 Secondary conversion processes

After a syngas is produced from gasification, it is cooled, cleaned of solids and sulphur (Figure 1) through various processes [51] and sent to the water-gas shift reaction [24], where the CO in the syngas is converted to H_2 and CO_2 using steam. Then, the hydrogen is separated from CO_2 using membrane reactors [50] and sent for purification using the pressure swing adsorption (PSA) process. The purified hydrogen is stored. An alternative prospective approach is to use chemical looping combustion to reduce CO and produce separate streams of hydrogen and CO_2. The hydrogen from direct chemical looping is also sent to the central hydrogen storage after cooling to remove water.

The methane and CO_2 produced using anaerobic digestion passes through an auto-thermal reformer (ATR), which has been reported to yield a product with fewer trace impurities than other coal-based hydrogen production processes, mainly due to the higher operating temperature generated by the oxidation step [51]. The produced hydrogen, which is part of a mixture containing CO and steam, is separated using an appropriate membrane reactor for this type of mixture [52].

The hydrogen from the high temperature electrolyser, which follows the combustion-to-electricity-to-hydrogen route [49,50], is directed to the central hydrogen storage.

2.6 Carbon capture and sequestration (CCS)

Although there are other pollutants, such as SO_2, NOx, Hg and COS, the emphasis of this system's design in the pollution control aspect is to address the concerns associated with increasing CO_2 emissions [6], which are mainly associated with carbon-based solid fossil fuels. Thus, the hydrogen from various gas streams, subsequent to cleaning and particle separation, is accompanied by CO_2, which can be stored [53]. Two paths for the CO_2 are envisioned here, as shown in Figure 1. The commercial route is already applied by several industries for using and storing CO_2 in various forms. The main challenge for using carbonaceous solid fuels in producing hydrogen is the disposal/storage of the captured CO_2 in an environmentally feasible manner [16]. The current commercial applications include industrial use of CO_2 in supporting large refrigeration systems, making dry ice, enhanced oil recovery, and various chemical manufacturing operations. Also some CO_2 produced in the system may be used for transporting solid fuels into high-pressure reactors. The remaining CO_2 is sent for large-scale underground storage [54]. Such processes are being implemented commercially in recent years through a process known as geological sequestration (GS), where the CO_2 is compressed and transported deep underground into aquifers, depleted oil and gas reservoirs and dried underground coal beds. Some large-scale CO_2 storage projects are already in operation and under construction, while others are the subject of feasibility studies [55].

The future route in Figure 1 for the CO_2 storage is aimed at two strategies still at the research stage. One involves a mineral storage where CO_2 is reacted with naturally occurring Mg and Ca containing minerals to form carbonates. This process has several advantages, the most significant of which is the fact that carbonates have a lower energy state than CO_2, which is why mineral carbonation is thermodynamically favourable and occurs naturally [56]. Thus the carbonates are stable and are unlikely to convert back to CO_2 under standard conditions. The CO_2 recycle or reuse is another option that involves metal oxides such as Fe_2O_3, ZnO and CaO to split CO_2 into CO and oxygen, for use in various processes [57]. The latter option in which CO_2 is split into CO and oxygen is an artificial photosynthesis process; it is a greenhouse-type concept for controlled feeding of biologically-engineered plants that can consume, in a controlled environment, high volumes of CO_2 to store carbon and emit oxygen [58].

There is an upcoming and promising third option of disposing CO_2, converting CO_2 into microalgae using sunlight and water, via algae-based artificial photosynthesis. Microalgae are microscopic photosynthetic organisms. They generally produce more of the kinds of natural oils needed for biodiesel extraction [59]. Autotrophic algae enable photosynthesis by utilizing light (from the sun or artificial sources such as light through fiber optic cables), CO_2 and water to grow the candidate algae (depending on the conditions available for growth). Heterotrophic algae use thermal energy from waste heat applications, CO_2 and nutrients derived from biogas effluents, leachate in landfills and waste water from fermenting processes.

2.7 Planned future extensions

Two sections in the proposed system in Figure 1 are intended for a planned future extension: (i) the upstream cleaning of feedstock (top right corner) and (ii) solids recycle coupled with a cement plant (bottom left corner). Upstream cleaning enhances the quality of feedstock thus improving the efficiency of various conversion processes [1] and also simplifies the separation of pollutants associated with solid fuels [2]. Some of the envisioned upstream cleaning process are (i) using a cartridge system, where all solid feedstocks are blended to form a uniform mixture containing a standardized composition, (ii) treating the feedstock with solvents to clean the fuel of unusable residue, (iii) blending of high-sulphur, high-grade coals with low-sulphur, low-grade coals and high-ash biomass (to avoid sintering), and (iv) upgrading low-grade solid fuels with pre-treatment using heavy oils [2]. Ash is among the most recycled solid within the system; after utilization it may be used to produce concrete blocks as part of the cement manufacturing extension plan.

The type of conversion technologies chosen in this work for hydrogen production and CO_2 capture and storage are based on the effectiveness of each technology, as determined by its demonstrated capabilities from industrial and research data. Thus the system is anticipated to be capable of handling several types of solid fuels at a given time and producing hydrogen in large quantities while delivering captured CO_2 in an environmentally and economically viable manner. As illustrated at the bottom of Figure 1, hydrogen represents a green means of energy distribution while CCS (in red) represents the potential to hinder the use of carbon-based solid fuels if not adequately implemented.

2.8 Status of hydrogen market in Canada

Hydrogen is mostly used in Canada at present in chemical industries. Approximately 35% of the hydrogen use is for chemical production, 24% for refining of oil, 23% for heavy oil upgrading and 18% for chemical process by-products [17]. Hydrogen is not yet a significant part of the direct energy system in Canada. Most of the hydrogen used in the chemical industry is produced from natural gas by steam methane reforming (SMR). The crude oil refining industry produces hydrogen by reforming more complex hydrocarbons available within the refining processes [60].

Because of its large fossil fuel resources, Western Canada dominates Canadian hydrogen production. Canada’s largest hydrogen plants are located in the oil-upgrading facilities of this region. Three plants in Alberta and one in Saskatchewan together produce nearly 790,000 tonnes of hydrogen annually [60]. The upgrading of heavy oil from the Alberta oil sands has recently been one of Canada’s fastest-growing

hydrogen demand sectors [15], with annual production predicted by some to rise to 2.8 megatonnes by 2020. Recent challenges to the global economies render such predictions questionable, unless economic recoveries occur quickly. Potential future environmental limitations also can affect such predictions. Electrolytic hydrogen production makes up an estimated five percent of Canada's supply [60].
The amount of surplus hydrogen (hydrogen produced that is not used at the generating site) produced in Western and Eastern Canada is estimated at 200,000 tonnes per year [60]. From an energy perspective, this amount of hydrogen is equivalent to 760 million litres of gasoline [17] or the equivalent to fuel one million light-duty fuel cell vehicles for a year.

3. Qualitative methodology and sustainability indicators

A qualitative methodology, which is partially quantitative, was introduced in our prior work [61], for evaluating the sustainability of energy systems involving hydrogen production from solid fuels. The indicators for each of the three dimensions of sustainability are chosen in this work, in the same manner as the previous work [61], so that they are mostly independent of the indicators in other dimensions, but related to them in the broader sense of the system's end product – hydrogen. This is a new methodology specific to this work in assessing the system's sustainability within the Canadian energy market. The methodology is developed by defining specific indicators whose values are assessed based on many other contributions in the literature with respect to each indicator. The methodology may be applied to sustainability assessments of similar energy conversion systems, provided appropriate variables and indicators are specified.
The index values for each indicator are related to other indicators depending on their definitions, and governed by the EEE platform – energy, economy and environment. The value of indices for each of the indicators is chosen based on the collective information obtained from an extensive literature review relating to the respective indicator. The index value ranges from 0 to 1 divided into 10 steps. Although index values are chosen based on an examination of pertinent data and information, the assignment is somewhat subjective. The expectations for a maximum value of 1 is kept very high in this work, so only very few elements within the system are capable of receiving a value of 1 for some of the indicators.
The term 'element' in this work means a natural resource such as solid fuels, or any other unitary item involved in the system. The term 'process' means an activity which involves more than one item in making a desired output; process types considered here include conversion processes, fuel handling processes, and carbon capture and storage processes. The term 'system' refers to the proposed system shown in Figure 1.
The main product of the system, hydrogen is considered to be the most advantageous alternative fuel for mitigating direct CO_2 emissions to the atmosphere [7] from carbon based solid fuels, while still providing the goods and services required by society. In Canada, hydrogen is not used extensively as a fuel, but is utilized presently in large quantities as a feedstock for various chemical processes in industries and oil refineries.
Sustainability for the proposed system is predicted based on the assumption that a hydrogen economy will be in place when this system is operational, which is likely at least 10 years from now [7].

3.1 Ecology indicators

In this work, ecological indicators [18] help in assessing information about ecosystems and the impact of human activity on ecosystems pertaining to the large-scale production of hydrogen. Here the ecosystem is considered as Canada and its energy market. Human activity involves implementation and operation of the proposed system to obtain hydrogen in large quantities. The values of these indicators specify the sustainability position of a particular element or process within the system along the ecological dimension. These indicators highlight the impact of each element or process on changes to the environment.

1. <u>Availability:</u> Sustainable availability of the element within Canadian market [1-7,54,62]. The highest value of 1 is assigned for such elements or processes that are available in the local market at competitive price and the lowest value of 0 is assigned for lack of availability, which in the current work is negligible since the elements and processes are selected based on minimum availability of all of them within Canadian or American markets. For example, fossil fuels such as coals and tar sands are mostly found in western Canada [4] and the coal market is bigger in the USA providing

ample supply for longer periods of time at very low costs. Similarly, for any process that is commercially available, the sustainability index will be higher.

2. Adaptability: Requiring less number of processes to acquire and process the element, minimizing waste generation [1,3,10,17,50,51]. A value of 1 is chosen if an element or process is highly adaptable and 0 for the least adaptable item in the system. Values for all items in the system fall in between 0 and 1, some having higher adaptability than others based on the review of respective elements. For example, ecological sustainability is higher for solids handling process in Canada than for gasification process, since the former is already an established industry serving the coal power plants in Canada [1,13].
3. Environmental capacity: How long in terms of time and material can the global ecosystem supply and support the element or process, without creating massive imbalances within the global ecosystem [4,6,13,15,16,63,64]. A value of 1 is assigned if an element or process can be sustained for a long time even with an increase in demand for it in the market place. A value of 0 is assigned if very little resources are available in the local market and they cause a high impact on the ecosystem. For example, a process which is capable of recycling its working materials is assigned a higher index than a process that has less probability for reusing some of its wastes or by-products.
4. Timeline: How new or mature is the element or process, weighted by its evolution [5, 24,54,65] within the market place. A value of 1 denotes that a process is well established and has greatly evolved since its creation, while a value of 0 denotes that the element is “fossilized” and the process has little chance for further improvement in functionality. For example, commercial gasification is a mature technology with small chance for major improvements or evolution, thus established and is assigned a higher value (0.7).
5. Material rate: Rate at which the element/process or products for and from the element/process can be procured [4,12,16,62,63,66,90], accounting for the effectiveness of raw material and product distribution networks. A value of 1 is assigned to the best network and 0 for the worst. For example, coals have higher material rate sustainability index (up to 0.9) than biomasses (up to 0.5), due to the well established network of mining and distribution.
6. Energy rate: Rate at which energy can be supplied by the element or process [4,62,67,68]. A value of 1 denotes a high energy supply rate and 0 a low energy supply rate. This indicator helps in assessing the ecological energy density for an element or process, the amount of energy available per unit volume of space per time period. For example, combustion processes have a very high energy rate compared to other process due to higher rate of chemical reaction. Coals have a very high energy rate in that they can deliver more energy per unit mass and time than biomasses.
7. Pollution rate: The rate of pollution or emissions of any kind associated with the element or process [1-4,16,45,56,69-71]. A value of 1 is assigned if there is very low pollution rate and a value of 0 if there is high pollution rate. For example, consider coal use either in air combustion or oxy-gasification. Since the technologies for pollution removal such as for sulphur compounds (SO_2, H_2S, COS) are well evolved, these processes merit a higher value than for CO_2 separation and storage, since it is still new and commercialization is yet to begin.
8. Location: How near the element/process is from the point of use [15,50,21,27,50]. A value of 1 is assigned if the source is very near to the point of use and 0 if it is very far (if it is outside the local market, i.e., for this work Canada and the northern USA). The system can be placed near to the main solid fuel source, which would be coals (which have high energy densities and still transfer more energy with CCS than other fuels). The other elements and processes are to be moved to the system’s geographical location, increasing the operating and maintenance costs of the system. Thus for coals and other mine-based solid fuels, low values are assigned in this work.
9. Ecological balance: Element or process that creates an imbalance in the local ecosystem. This measure also indicates the level of recyclability or reuse of the element or process [68,72,73]. A value of 1 is assigned if most of the element or process is recyclable or reusable and a value of 0 is assigned if there is no achievable recyclability. For example, fossil fuels score a 0 in this regard whereas renewable solid fuels such as biomass or MSW score a higher value, which depends on the availability as well. Regarding processes, air-combustion of fossil fuels emits CO_2 along much

nitrogen (thus receiving a low value due to the imbalance it causes in local energy consumption, since higher compression energy is required for CO_2 sequestration or even for CO_2 separation). Oxy-combustion or gasification, on the other hand, produces a relatively pure CO_2 exhaust stream, enabling low energy capture (thus a higher value is assigned since the local energy imbalance is minimal).

10. Endurance: Element work load or demand factor and a process requiring equipment maintenance [1-4,68,72,73]. A value of 1 is assigned if the element or process has high load and demand with lower maintenance and a value of 0 is assigned when there is high maintenance irrespective of high or low load. For elements such as fuels that require high equipment maintenance, a lower index value is assigned for this sustainability indicator.

3.2 Sociology indicators

In this work, sociology indicators help in assessing impacts on the social system if the proposed hydrogen system is implemented, in order to guide intervention or alter the course of social change [74]. Here the social system represents the communities within Canada that will benefit directly and indirectly from the operation and products of the hydrogen system. The expected changes to the social system from implementing the proposed hydrogen system are considered via the 10 indicators that follow. The values of these indicators, which range from a high of 1 to a low of 0, specify the sustainability of an element or process within the social system, thus helping to avoid any negative or undesirable changes.

1. Economics: Economic and financial benefits from the element or process [5,10,11,20,21,50,54,60,67,75-77]. A value of 1 is assigned if maximum net economic benefit derived from the final product (hydrogen) and a value of 0 is assigned when there is a net economic loss from transforming solid fuels into hydrogen. For example, commercial (large-scale) gasification shown in Figure 1 provides better overall economic benefit than solar thermal gasification due to it exhibiting a higher volume of hydrogen production in less time than is possible when using commercial gasification.
2. Policy: Canadian government policies and implementation trends [1,5,7,10,13,15-17,63,64]. A value of 1 is assigned if the policies and implementation strategies support the sustainability of an element or process and a value of 0 is assigned if they act as hindrances. Values are chosen based on advancements in technology in dealing with energy, environment and economics of processes and ecological sustainability of solid fuels to help in obtaining the final product of hydrogen. For example, a government initiative to increase funding for research on biochemical routes, to produce alternate transport fuels, helps in improving the sustainability of such processes as anaerobic digestion [47] and algae-based biodiesel production [59].
3. Human resources: Level of direct human work input involved in procuring, manufacturing, installing and operating an element or process, within the Canadian market [5,70,68,72,73,90]. A value of 1 is assigned if more human work is involved, owing to the job creation and resulting economic benefit for the society. A value of 0 is assigned if no direct human work is involved with an element or process. For example, solids handling processes and waste disposal involve more human labour than primary or secondary conversion processes (except during installation and maintenance).
4. Public opinion: Public opinion regarding the nature and operation/behaviour of an element or process [78-81,90]. A value of 1 is assigned if the majority of the population have a positive opinion relating to an element or process and a value of 0 is assigned if there is a negative opinion. For example, CO_2 emissions particularly from burning fossil fuels have been highlighted by the media and government bodies as the main cause of a rise of mean earth's surface temperature [6]. So, any element or process which does not emit CO_2 or reduces it concentration in the atmosphere, is assigned a higher value since generates positive public opinion. In the bigger picture, public opinion often transforms into government policies, which can lead to support for measures that curb harmful emissions, especially in Canada.
5. Environmental obligation: Social expectations regarding the environmental obligation of an element or a process and its by-products to be benign to the environment in which society functions

[6,16,45,50,54]. A value of 1 is assigned if the operation and by-products of the element/process is environmentally benign and a value of 0 is assigned if a process or element is necessary to the system's operation but is capable of harming the environment without another set of processes for protecting the environment. This indicator encourages the elimination of any process that requires such additional measures to protect the environment or that it be used only if no alternative can be found. For example, converting CO_2 into biodiesel using sunlight or nutrients from the biogas by-product associated with using algae is environmentally friendly in that it not only consumes some of the CO_2 emitted from burning of fossil fuels but also provides an alternate transport fuel, thus reducing additional emissions of CO_2. So, converting CO_2 to algae is assigned a higher social index value than other CO_2 sequestration methods that require further processes which in turn create more ecological imbalance (underground CO_2 storage).

6. Living standards: Impact of an element or process on human living standards (focussing on basic requirements such as food, clothing and shelter) [54,82]. A value of 1 is assigned if an element or process within the system improves human living standards indirectly. A value of 0 is assigned if an element or process does not improve basic living standards. For example, coals are assigned a higher index than biomass due to their higher energy densities, which helps in producing more hydrogen; this in turn can provide additional goods and services compared to biomass, thereby improving basic human living standards. Even with high energy and economic penalties for pollution control measures, coal can still produce more hydrogen than biomass [54].
7. Human convenience: Impact of an element or process on human convenience (higher living standards and comforts that are not necessary like basic living standards) [54,82]. A value of 1 is assigned if an element or process within the system helps in providing human comforts and a value of 0 is assigned if an element or process does not provide human comfort, through additional hydrogen production. The index values for solid fuels are similar to those for the previous indicator (#6). But for some processes, the index value may be lower, e.g., if more fuel is used due to increased secondary and environmental protection process loads in producing hydrogen.
8. Future development: Possibilities for future economic and social growth based on the nature of an element or process [1-6,60,67,75-77]. A value of 1 is assigned if using the element or process increases the possibility for societal development. A value of 0 is assigned if using the element or process within the proposed system does not provide opportunities for societal development, even in the local community. The system involves many processes that produce several by-products in producing hydrogen. These are given higher index values since the by-products help in increasing the overall economic and social income to the local community.
9. Per capita demand: Impact of population/customer demand on producing hydrogen with the element or process, affecting the ability to carry out the process sustainably [6,54,82]. A value of 1 is assigned if fewer industries use the element or process, thereby increasing market availability and, possibly, price competitiveness. A value of 0 is assigned when the element or process is used by many industries, which hinders availability and can reduce sustainability. For example, coals are mostly used for power generation and in steel industries, based on its per capita availability it is assigned a high value. But biomass per capita availability is small and is mostly used in co-combustion processes or as manure, reducing the per capita demand sustainability index.
10. Lobbying: External influences on the impact of an element or process, through political and economic lobbies, that can affect government policies related to sustainability [16,17,54,63,65,66,83]. A value of 1 is assigned if the process or element has effective lobbying and a value of 0 is assigned if no lobbying is attempted. Negative lobbying is not considered at this point. For example, the coal industry is well established economically and is engaged in political lobbying to maintain its use within the Canadian energy market and to promote government policies that support the coal industry [83]. In recent years, green energy programs have received extensive lobbying due to their potential long-term contributions in mitigating global warming. So, elements or processes associated with green energy policies (such as anaerobic digestion, plasma gasification, supercritical water gasification, CO_2 to algae) are assigned higher index values.

3.3 Technology indicators

In this work, technology indicators help in assessing the knowledge, design, performance and production aspects of an element or process selected for the hydrogen system, providing an engineering perspective. The indicators are chosen so that they assess the technical capabilities of each element in the system on the same level. The values of these indicators specify the sustainability of the system and its components, such that the technologies chosen are examined for energy affordability, environmental limitations, commercialization possibilities and potential progress with respect to the production of hydrogen.

1. Net energy consumption: Energy requirement of the element to bring it to the point of use and energy required for operation of processes [20,24,30,31,36,39,51,54,60,68,76,82]. A value of 1 is assigned if the element or process requires little energy and a value of 0 if it requires a great amount of energy. For example, processes that generate energy have higher index values (primary conversion, electricity generating and hydrogen production processes) than those that consume energy during their operation.
2. Exergy: Relative exergy of the element or process with respect to the system and the environment [54,62]. A value of 1 is assigned for an element with high exergy or for a process that has lower exergy destruction and a value of 0 is assigned for an element with low exergy or for a process with high exergy destruction. For example, combustion processes have high exergy destruction compared to gasification processes and subsequent hydrogen production processes. Thus combustion processes within the system are assigned lower technology index values for exergy.
3. Efficiency: Efficiency (ratio of desired output to input, considering both energy and exergy) of every element or process and related technology in obtaining the final product of hydrogen [68,72,73]. A value of 1 is assigned for processes that have very high efficiencies (above 0.9) and a value of 0 is assigned for processes that have very low efficiencies (below 0.1). For example, commercial electrolysers have between energy efficiencies ranging typically from 0.5 to 0.7 [54]; a value of 0.7 is assigned to them, which is the highest value for efficiencies of all the items in the system.
4. Design: Impact of design of a process or an element on sustainable operation of the system [7,10-13,17,22,25,50]. A value of 1 is assigned for the best design, taken to be a design that, among other factors, improves the overall performance of the system and minimizes waste generation. A value of 0 is assigned for the worst design of a process. No process or element in the current work is assigned a value of 0 is given the types of processes selected for inclusion in the system design. For example, consider USS gasification, which is still in the research phase but has significant future potential. This process is assigned a low index value (0.3) since it is not a fully mature design and is likely while it develops to cause problems in the overall system or with other conversion processes in it.
5. Research: Impact of research on future developments of a process or an element that affect the ability of the system to produce hydrogen sustainably [7,10-13,17,22,25,50,54]. A value of 1 is assigned for an element or process with high probability for successful research and a value of 0 is assigned when there is a low probability for research and advances. For example, utilities like solids handling and ash and slag collection have a low probability for intensive research that will help in improving the system's performance, so they are assigned a lower index value. For plasma gasification and CO_2-to-algae conversion processes, the amount of research, due to technology prospects and incentives, is sufficient to merit higher index values.
6. Demonstration: Capacity for demonstration of the impact of an element or a process in contributing to hydrogen production in the system [3,54,60,84,85,86,87,88]. A value of 1 is assigned if the process or element is has already been demonstrated (as for commercially established technologies). A value of 0 is assigned if there is a need in the future for demonstration to establish the capability of the technology. For example, commercial gasification and solids handling processes have high index values since they are more mature than the ones that are still undergoing research and development, such as CO_2-to-algae conversion processes, supercritical water processes and USS gasification.
7. Commercialization: Potential for process or element technology to become commercially viable, enabling sustainable large-scale operation within the system [1-5,11,13,24,34,51,54]. A value of 1 is

assigned for processes or elements with excellent potential for commercialization and a value of 0 is assigned for processes with little potential for commercialization. For example, USS gasification is assigned a low value (0.4) since it has very limited potential for commercial development due to size constraints (i.e., large-scale operation will result in very low efficiencies thus increasing operating costs). Commercial gasification is assigned a high value (0.9) since it operates commercially on a large-scale and is the fastest growing segment within the coal industry due to its ability to produce synthetic gases for various alternative fuels programs [51].

8. Impact: Impact of actual process or element on sustainability of the system for producing hydrogen [11,13,20,34,36,41,46,47,54,67,68]. A value of 1 is assigned to processes or elements that have very high impact on the system's performance and a value of 0 is assigned to those that have very low impact. For example, within the commercial gasification process (Figure 1), the air separation unit (ASU) is assigned a higher value (0.8) than the ash handling system (0.4) because the ASU is crucial to a high-efficiency solid-to-gas conversion as well as effective downstream CO_2 capture. The ASU therefore has a significant impact on improving the overall efficiency of the system for producing hydrogen, whereas the ash handling system, although essential, does not impact the system efficiency as much as the ASU.
9. Evolution: Capacity for process technology to improve, adapt and grow in the Canadian energy market place [4,5,7,10,13,54,63,70,83]. A value of 1 is assigned to processes that have high opportunities for evolving to increase in efficiency and decrease in operating and maintenance costs, while a value of 0 is assigned to processes with little opportunity for such development. For example, commercial gasification has very little chance for evolution and is thus assigned a lower value (0.3), whereas supercritical water gasification is assigned a high value (0.7) since it is is expected to evolve into an efficient process for large-scale hydrogen production that is useful for effective disposal of sewage water [46].
10. Environmental limitations: Limitations of process technology arising from harmful impact on the environment while operating within the system [6,15-17,35,45,50,86,89]. A value of 1 is assigned to processes with few limitations in operation due to damage caused to the environment, while a value of 0 is assigned to the processes with high limitations in operation due to their environment impacts. For example, devices that contribute to pollution control within the system, such as the ash collector, syngas cleaner and membrane separator, have high index values since they are subject to few environmental limitations in their operation and they contribute to environmental preservation.

4. Sustainability of system components

The first set of results or sustainability index values are described for different components within the proposed system in Figure 1. The sustainability indices are plotted figures 2 to 8 on a percentage basis for different aspects of the proposed system, as sustainability triangles with three axes: techno-, eco- and socio-centric. The index values for elements such as each solid fuel are averaged across the 10 indicators in each sustainability dimension. For more complex devices like conversion processes (gasification, anaerobic digestion, etc.), the average index value of all the components within the sub-systems or processes is evaluated first for each indicator and then averaged across the indicators within each dimension. The maximum value for the sustainability indices in figures 2 to 8 is less than 0.8 (i.e., 80%). The averages are evaluated as simple means. Averaging sustainability indices may not provide the exact impact on system sustainability of indicators and system components, but it does provide a broad understanding of the impact on the sustainability of the system.

The values for each of the specific indices are shown in Tables 1 to 3 in the appendix. Discussions within each dimension for every indicator are based on the index values in Tables 1 to 3.

4.1 Sustainability of coals

Since coals are already an established fuel for the electricity market, its sustainability is above average. Of the total coal supply in Canada, 77% is used for electricity generation [4] in over 60 coal combustion power plants [1] totaling over 17 GW of electricity generation capacity. Of this capacity, 44% is located in from Ontario, 34% in Alberta, 10% in Saskatchewan, 7% in Nova Scotia, 3% in New Brunswick, and 1% in Manitoba, based on data for the year 2004. About 8% of the coal supply is used by industries for coking and gas manufacture. Based on Canadian coal reserves [16], the potential applications for coal are not being realized currently beyond electricity generation and limited industrial use [90], because of the existence of natural gas and crude oil resources which have a higher market value than coal and are in demand in external markets.

From Figure 2, it is evident that all coals have less than average ecological sustainability, with anthracite at about 31%. This is largely due to lower environmental capacity exhibited by coals and the ecological imbalances their use can cause. All coals have the same values for techno- and socio-centric dimensions.

Within the ecological dimension, coals score high (about 70%) in availability, material rate and endurance and low (less than 20%) in adaptability, pollution rate and ecological balance. Industrial residue is a mix of inorganic solid wastes from various industries that may serve as fuel in combination with coal or biomass. Industrial residue is assigned higher index values in terms of pollution rate and ecological balance.

Within the sociological dimension, coals are assigned high scores for per capita demand and lobbying and low scores for public opinion and environmental obligation. Industrial residue scores the highest for future development and the lowest for lobbying, and has an average index value of 47%.

Within the technological dimension, coals score high on exergy and technology impact do not receive low index scores for any of the indicators, all of them being above 50%. This result demonstrates the characteristics of industries associated with coals: power generation, steel manufacturing, and oil companies (at least in western Canada).

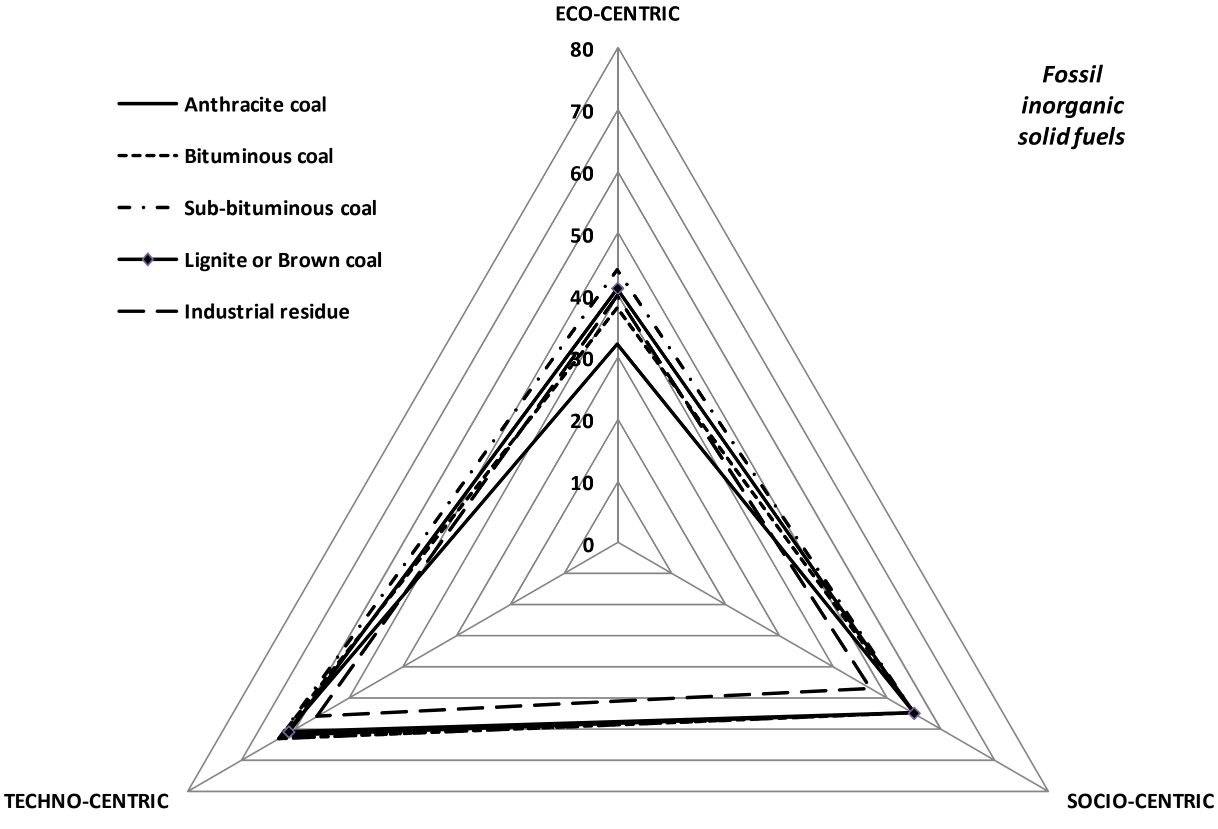

Figure 2. Sustainability indices (%) for solid fossil fuels and inorganic fuels used in the system

4.2 Sustainability of biomass

Biomasses are used in co-firing and co-gasification applications in Canada. Few units converting biomass and MSW to electricity are in operation in Canada, with less than 50 MW of electrical generating capacity [60,67]. These plants produce less than 5% of the total electrical energy used in the province of Ontario. This low utilization is due in part to a lack of higher conversion potential with biomass fuel, because only one energy conversion technology is used at a given time within the facilities operating in Canada.

Figure 3 shows the averaged sustainability triangle for all the biomasses and system solid wastes (solid wastes that are generated after primary and secondary conversion processes within the system). Biomass from farms are assigned a higher index value (10% higher) than biomass from forests, due to a higher average score in techno-centric dimensions. This result is mainly due to the nature of the feedstock, which is drier and bulkier than forest biomass, thereby enabling higher values for evolution, commercial and net energy consumption indicators.

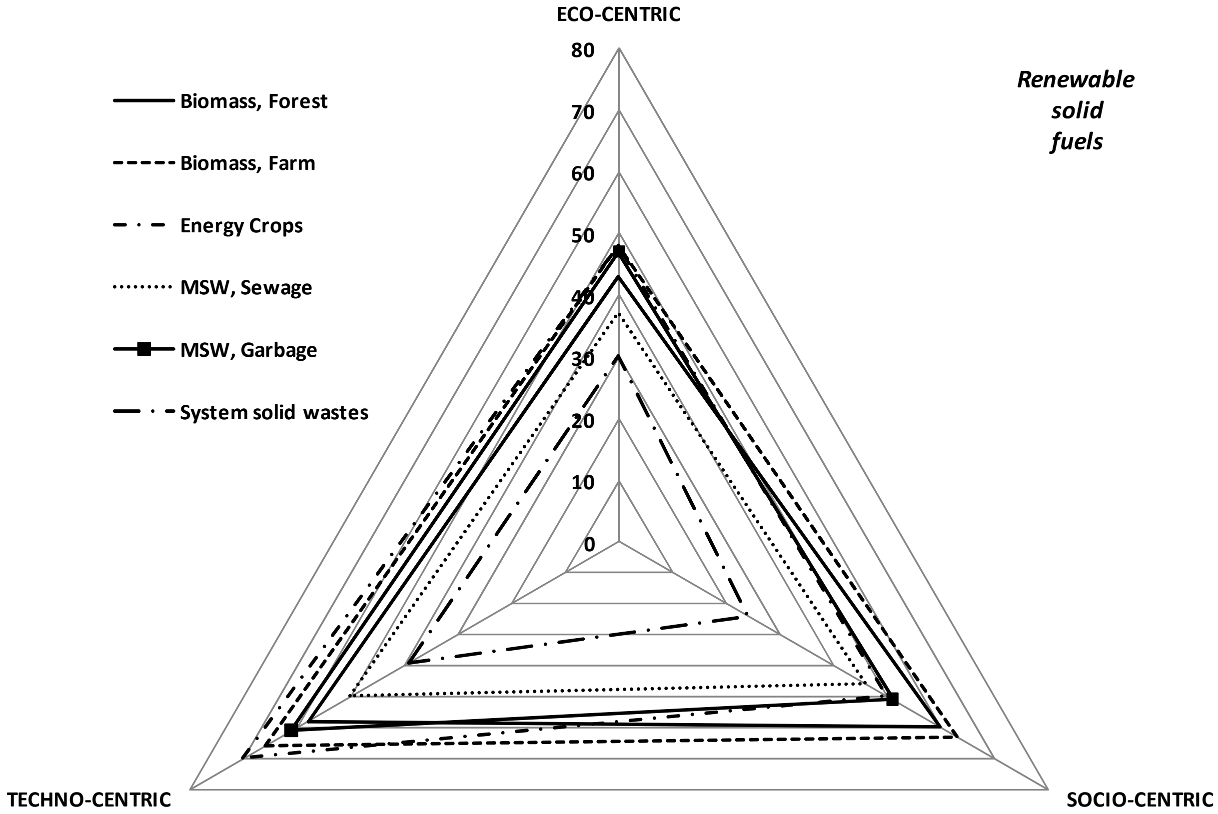

Figure 3. Sustainability indices (%) for renewable solid fuels used in the system

Within the ecological dimension, farm biomass, energy crops and MSW-garbage have the same average index values. MSW-sewage has a lower value due to low index (10%) for adaptability, pollution rate and ecological balance. System solid wastes have very low indices for all dimensions since they have the lowest energy rate, economics and exergy.

Within the sociological dimension, MSW-garbage has a 10% lower value than biomasses, since biomasses have high values (over 70%) for economics, public opinion and lobbying. The characteristics of system solid wastes cause them to receive very low values for all indicators in this dimension. By recycling these system wastes, the sustainability of waste management can be improved. In future waste handling regulations will likely become more stringent, making it worthwhile to improve sustainability now.

Within the technological dimension, most of the biomasses are similar and are assigned the highest values of all the three dimensions. This is due to the above-average values scored by biomasses, energy crops and MSW-garbage. Energy crops are assigned the highest value (90%) for environmental limitations in the use of technology relating to its processing.

The overall sustainability score of biomasses can be expected to increase once a market and demand are established.

4.3 Sustainability of fuel handling processes

Solid fuels arriving at the system require temporary storage, drying, crushing/milling and internal transport mechanisms. The handling of solid fuels consumes some energy with operation and maintenance costs and is vital to the functioning of a system using solid fuels. Due to the availability and widespread use of solid fuels [91], their handling is mature. Upstream processes (in Figure 1) involve cleaning, blending and upgrading of solid fuels to enhance the quality of the feedstock, thus improving the efficiency of various downstream conversion processes [1] and also simplifying the separation of associated pollutants [2].

In Figure 4 the sustainability index for the three dimensions are shown for the five different fuel handling processes. Except for storage, all processes are assigned values close to 70% for ecological sustainability. The drying process has the highest of technological sustainability index (60%) since drying of solid fuels is essential for most conversion processes. Some exceptions are supercritical water gasification and anaerobic digestion.

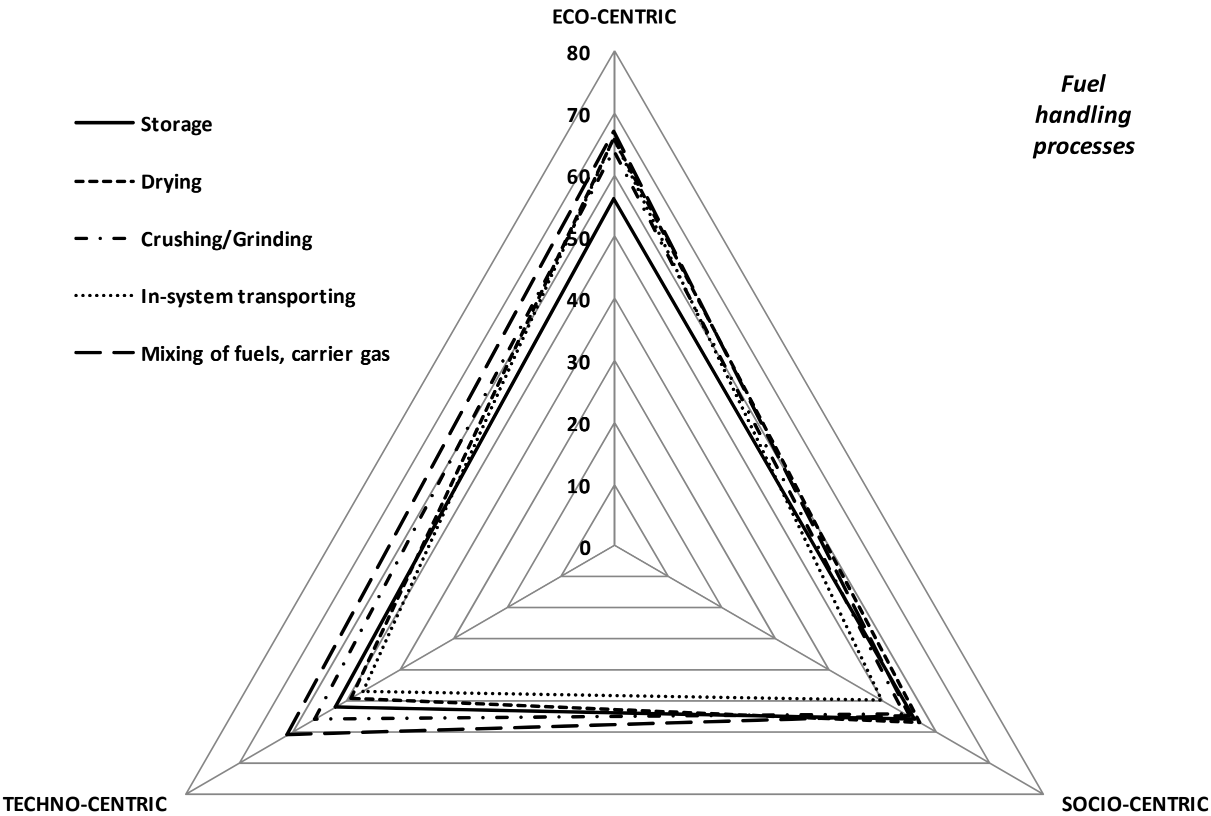

Figure 4. Sustainability indices (%) for fuel-handling services within the system

Since fuel handling processes are essential to the effective operation of any energy system that use solid fuels [24], it is likely more advantageous to improve the performance of drying and storage aspects of fuel handling since one affects the other. These two processes affect the crushing and grinding operations which in turn affect the in-system material transport on conveyor belts or in pipes.

4.4 Sustainability of gasification processes

Five different gasification processes are included in the proposed system in Figure 1. Of these, commercial gasification and plasma gasification have capabilities for large-scale production of synthetic gas. Of the total hydrogen production from the system in Figure 1, up to 60% is expected to be produced from syngas obtained using the five different gasification processes.

Large-scale commercial gasification is becoming established in the US as a means of producing syngas for various uses, the most common of which are power generation [92] and the production of substitute natural gas (SNG). Four commercial gasification technologies capable of producing syngas from five different feedstocks are identified in the commercial gasifier database [93]. The gasification technologies of Shell, Sasol Lurgi, GE Energy and others have been compared and their details have been analyzed by the US National Energy Technology Laboratory [27]. The commercial capacity of the Shell process has increased recently (from 21% of the gasifier market in 1999 to 28% in 2007) while that for the GE Energy process has decreased (from 39% in 1999 to 31% in 2007).

Sustainability index values in three dimensions are shown in Figure 5 for the five different gasification processes. Except for the ecology value, supercritical water gasification has higher values than other gasification processes in the technology dimension, due to its advantages regarding exergy, commercialization, impact and environmental limitations.

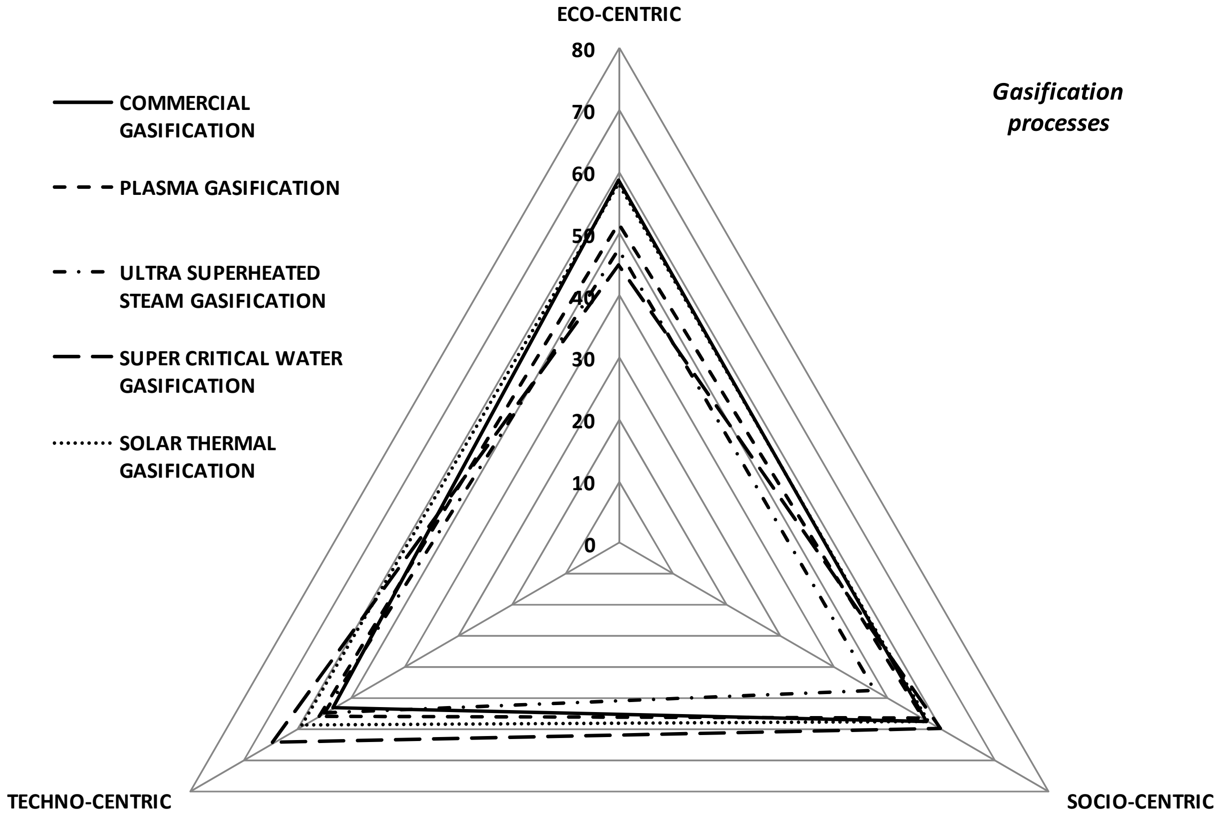

Figure 5. Sustainability indices (%) for selected gasification processes within the system

Commercial gasification, although capable of producing large quantities of hydrogen, has a lower sustainability ranking than some of the newer gasification processes, mainly due to its low index values for the ash handling system and the syngas cooler within the technology indicators. Commercial gasification is assigned a high value (0.6), equal to that of solar thermal gasification, for the ecological dimension., Since Canada does not yet have any solid fuel-based commercial gasification facilities, the index values are based on data from the US market, to which an eventual Canadian market may be similar. Nonetheless, there is however a pilot-scale high-pressure (up to 20 bars) demonstration unit at the CANMET Energy Technology Centre in Ottawa [1]. Also, a petroleum-based 1025-MW capacity gasification plant is under construction at Long Lake, Alberta using the Shell gasification technology [93], and a gasification plant with a 40,000 barrel per day capacity is being developed at the pre-feed stage for commissioning by 2014 at Fox Creek, Alberta by Alter NRG [94].

Considering only the index values of gasifiers in each of the five subsystems, the commercial large-scale gasifier scores the highest (above 0.6, as seen in Tables 1 and 2) in eco- and socio-centric dimensions while the plasma gasifier scores high in techno-centric sustainability, owing to its rapid developments and commercialization potential. Ottawa City Council issued a letter of intent in 2008 to PlascoGroup to build, own and operate a 400 tonne-per-day waste conversion facility using plasma gasification technology [84]. Similar facilities by the PlascoGroup are planned in Vancouver, British Columbia and Red Deer, Alberta [84]. Plasma gasification technology was developed by Westinghouse Plasma Corporation, which is now wholly owned by the Canadian company Alter NRG. An increase in commercial potential for plasma technology in the near future is suggested by recent reviews of general plasma technology providers [78] and the Alter NRG/Westinghouse technology [95], particularly for converting municipal solid wastes in large cities across developed countries to useful syngas while applying CCS.

4.5 Sustainability of primary conversion processes

There are four primary energy conversion processes within the proposed system in Figure 1: gasification, direct chemical looping, anaerobic digestion and pressurized fluidized bed combustion. Sustainability measures for these are compared in Figure 6. Some of these processes are already used at commercial scales in Canada for various products, while other technologies in the proposed system have not yet achieved commercial viability, including chemical looping combustion (both syngas based and direct), ultra-superheated steam gasification, solar gasification and ultra-super-critical water gasification. These latter processes are still in the research phase of development, and in many instances may become commercial, although the timing depends on their potential advantages and corresponding demands [23] as well as other factors.

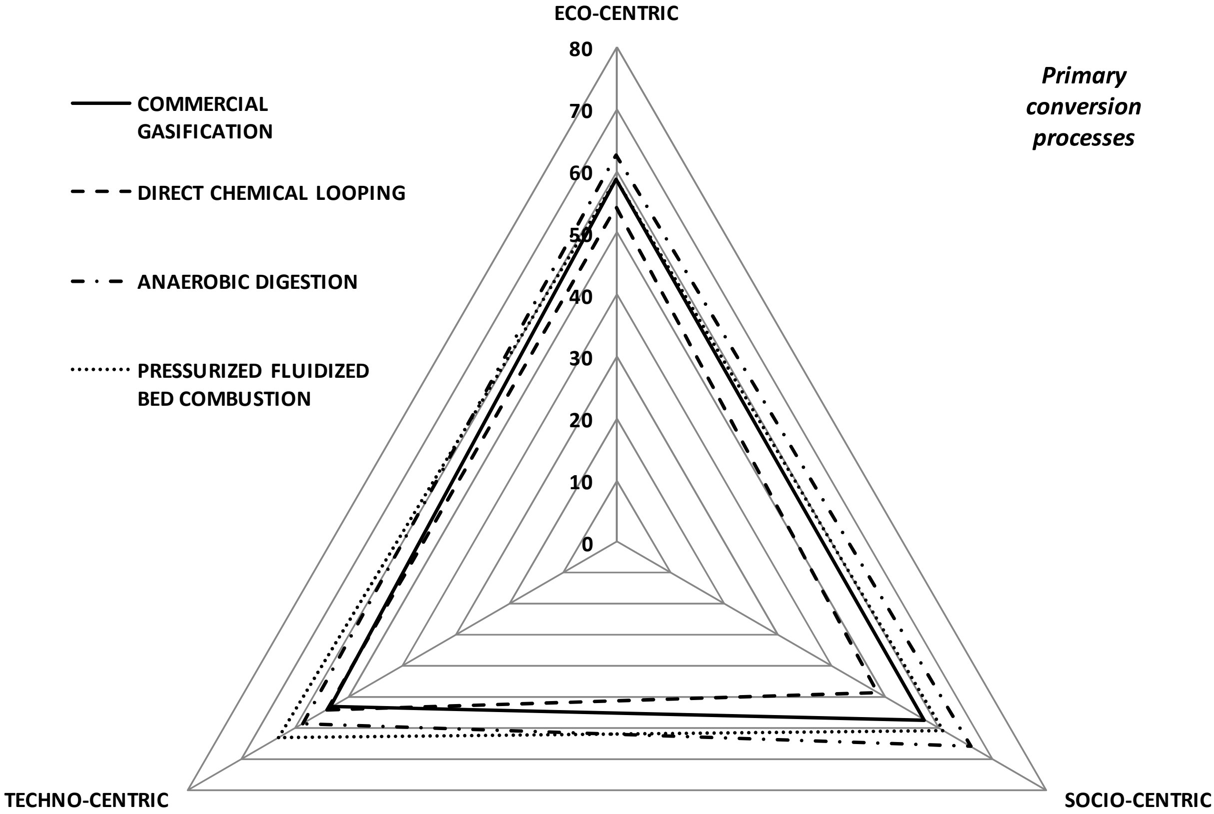

Figure 6. Sustainability indices (%) for selected primary energy conversion processes within the system

In Figure 6, anaerobic digestion exhibits good sustainability in all three dimensions considered compared to other conversion processes. Anaerobic digestion is part of an established co-production industry in Europe with over 3400 plants (both on- and off-farm) across 10 countries with a total electrical generation capacity of 700 MW [85]. The AgSTAR Digest in 2006 listed 82 operating digesters in the US [96], and 19 in start-up or construction stages. Only approximately 1% of the on-farm anaerobic digestion market has been developed, leaving a substantial untapped resource for generating electricity and a potential business opportunity for increasing farm income [96].

In Canada, and Eastern Ontario in particular, the economics of using agricultural residue and energy crops in anaerobic digestion are not viable at present [47]. A report for the province of Ontario [87] concluded that on-farm anaerobic digestion systems smaller than 300 kilowatts (applicable to farms with greater than approximately 3800 dairy cattle or 970,000 poultry) are not financially feasible with electricity prices below CAD 0.14 per kWh or without off-farm inputs. Incorporating off-farm organic material at a rate of 25% of on-farm organic material, improved the financial feasibility by increasing biogas production and offering the potential for tipping fee revenue [87]. Ontario Power Generation offers financial incentives to farmers who generate electricity from biogas, paying them about CAD 0.12 per kWh. However, this rate is subsidized, as it is higher than the market value of electricity, which varies in Ontario between 6 to 8 cents per kilowatt hour.

Compared to other primary conversion processes, direct chemical looping exhibits poor sustainability in the socio-centric dimension, since it has low index values for policy, human resources, environmental obligation and per capita demand. These scores are low due to direct chemical looping being in its infancy in the energy conversion industry [42]. This process is widely used in steel manufacturing but not in the hydrogen production sector. Technical advances are required to improve the social aspects of sustainability of direct chemical looping.
A combustion-to-electricity-to-hydrogen route may contribute up to 10% of the total hydrogen produced by the system in Figure 1. Although fluidized bed combustion is commercially established globally, the particular process intended for use in the proposed system is the advanced pressurized fluidized bed combustion process developed by the US Department of Energy and industry partners [97]. This particular process is still under development, but is entering the demonstration stage.

4.6 Sustainability of secondary conversion processes
Secondary conversion processes separate hydrogen from other gaseous elements, and the sustainability indexes for five such processes are compared in Figure 7. Water-gas shift (WGS) reactions use catalysts that have been commercially developed for use by the petrochemical industry [98,99]. Presently, there is renewed interest in the water-gas shift reaction because of its importance in reforming hydrocarbon fuels to hydrogen [25]. The WGS process is mostly used with gasification processes, and thus is part of that industry in Canada. It is observed in Figure 7 that the WGS reactor exhibits lower sustainability on socio- and techno-centric dimensions, since the WGS reaction is endothermic, and has low exergy and high net energy consumption.

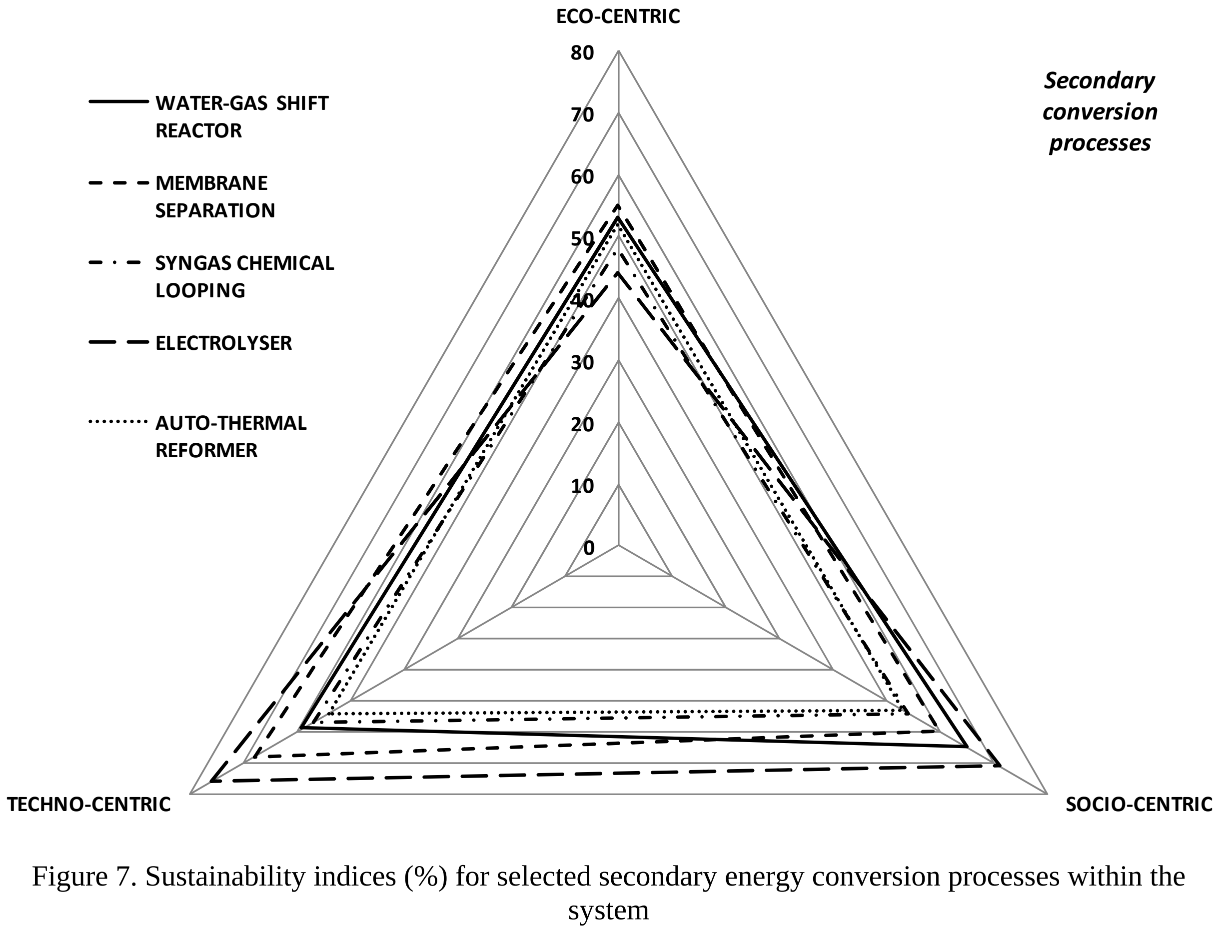

Figure 7. Sustainability indices (%) for selected secondary energy conversion processes within the system

Gas separation using membranes of various kinds, primarily differentiated by the membrane material, is a rapidly evolving field [100]. The most common commercial materials for membranes include metallic, ceramic and polymeric substances and, recently, carbon-based nanotubes or pores in compact grid arrangements [101]. From the comparison in Figure 7, it is evident that membrane separation has an

increasing commercial potential and impact, is evolving rapidly and has low environmental limitations, leading to its high index values (above 0.8) for these indicators within the techno-centric dimension.
In syngas chemical looping (SCL), the syngas produced from the gasifier, containing mostly CO, H_2, CO_2 and CH_4 [102], reduces a metal oxide (such as Fe_2O_3) to the constituent metal (Fe and FeO). In Figure 7, syngas chemical looping is seen to have lower sustainability in all three dimensions (less than 0.6) due to its low values for certain indicators. Within the ecological dimension, this process has low values (less than 0.3) for availability, adaptability and location (in Tables 1 to 3) due to its non-commercial state. But is also has possibilities to improve its sustainability index with market driven research. Within the socio-centric dimension, SCL is assigned a low value for human resources, again due to its non-commercial aspect of this process; this index value is likely to increase with commercialization to a value higher than 0.6. Recently, Alstom Corporation [103] concluded that chemical looping combustion is the lowest cost option for CO_2 capture when using coal for energy. Commercialization of this technology for CO_2 capture is being pursued rapidly by the US Department of Energy [103].
Electrolyser research and development in Canada and elsewhere is advancing somewhat in parallel with fuel cell research and development, as some aspects of functionality can be interchanged [64,76]. It is observed in Figure 7 that the electrolyser outperforms all other secondary conversion processes in producing hydrogen, from socio- and techno-centric dimensions. This is because of its high efficiency and related benefits, and the amount of academic and industrial research currently underway to improve electrolyser performance and reduce manufacturing costs. The assigned index value for economics for electrolysers in Table 2b is high (0.9), based on a comparison of the hydrogen price from high-temperature electrolysis process with other hydrogen production methods in operation or being developed.
Auto-thermal reforming (ATR) uses oxygen and carbon dioxide or steam in a reaction with methane to form syngas [104]. The reaction takes place in a single chamber where the methane is partially oxidized. The reaction is exothermic (releases thermal energy) due to the oxidation process. The ATR process is widely used in natural gas plants and oil refineries in western Canada [62]. The lower index values in Figure 7 for this process are mainly due to its average performance for all the sustainability indicators, resulting from limited markets and future prospects.

4.7 Sustainability of CO_2 sequestration

The International Energy Agency [54] recently compared energy resource types, conversion technologies and associated policies based on two scenarios (see Figure 5): (1) the ACT Map scenario of the IEA, which implies adoption of a wide range of technologies with marginal costs of up to USD 50 per tonne of CO_2 saved when fully commercialized, and (2) the BLUE Map scenario, which requires deployment of all technologies involving costs of up to USD 200 per tonne of CO_2 saved when fully commercialized. These scenarios are compared to reductions in CO_2 levels for a baseline scenario which accounts for CO_2 emissions reaching 62 gigatonnes (Gt) of CO_2 in 2050; this emission level represents a 130% increase from 2005 levels and is considered unsustainable [54]. The baseline scenario reflects developments likely to occur with energy and climate policies implemented to date. While the ACT scenarios are demanding, the BLUE scenarios depend on urgent implementation of unprecedented and far-reaching new policies in the energy sector [54], which will take more time and effort to implement than the ACT scenarios. The discussions in section 2 on CO_2 capture and separation suggest means of dealing with this CO_2.
Four options for sequestering the CO_2 are discussed in this work, and their sustainability is shown in Figure 8. Storing CO_2 underground is the current short-term solution preferred by several countries including Canada and the USA, who have jointly undertaken one of the largest CO_2 disposal operations in Winnipeg, Canada [55]. Although has been carried out at a commercial scale, this initiative appears not to have been comprehensively planned and balanced with respect to all relevant parameters in terms of eco- and techno-centric sustainability dimensions. Two main issues reduce the sustainability of this process: (i) compressing CO_2 beyond 130 bars, which is necessary to transport hydrogen as a liquid in pipelines across great distances, is expensive financially and challenging ecologically, and (ii) the volume of CO_2 compressed from all CO_2 emitting utilities is much higher than the volume of underground geological space available, that is capable of storing gases like CO_2 without impacting ecological balances [6].

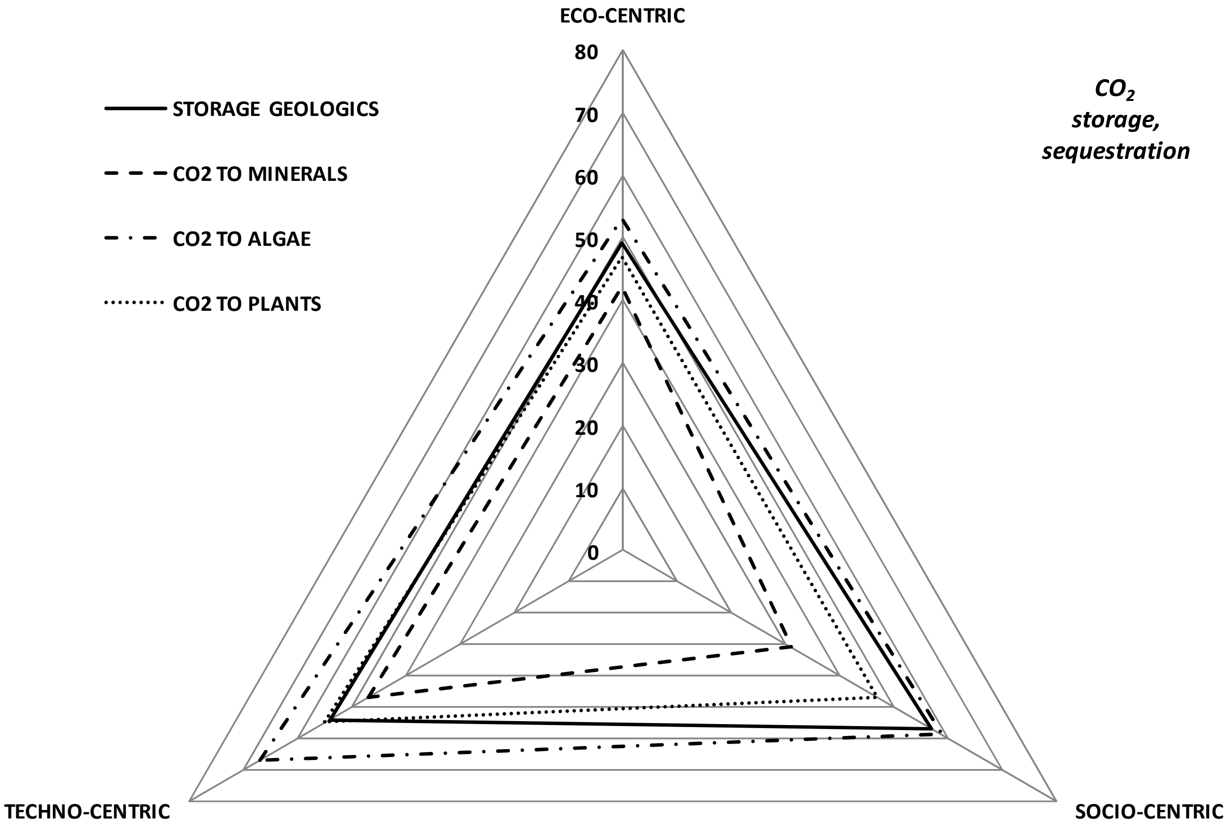

Figure 8. Sustainability indices (%) for CO_2 storage options as part of the CCS operation associated with the proposed system

Similarly, CO_2 conversion to minerals like calcium or magnesium carbonates, although easier to handle than gaseous CO_2, has an output volume that is several times the input volume, making it the least sustainable option for CO_2 sequestration. These challenges are reflected in the assigned corresponding indicator values across the three dimensions.

CO_2 conversion to algae, although in the initial stages of commercial development, has greater potential to become a sustainable option for converting CO_2 to biodiesel. The process utilizes an appropriate algae, and requires light and water [59]. This process is more efficient and faster than CO_2 conversion to plants through artificial photosynthesis in large greenhouses, allowing it to be assigned relatively high values for techno- and socio-centric sustainability indices.

Having carbon capture and sequestration options as part of the system provides better overall system sustainability, even though the system incorporates coal as one fuel source. This system is likely most advantageous during the transition phase from a hydrocarbon to hydrogen economy.

5. Sustainability of the proposed system

The discussion in the previous section is based on average values of indices across subsystems and indicators. In this section, average values of the six categories of processes mentioned in section 1 across 10 indicators in each of the sustainability dimensions are discussed, in order to develop some inferences regarding the sustainability of the proposed system.

First, however, a simple background on the system's prospects is provided. When the demand for hydrogen energy becomes large in Canada, systems like the one proposed in this work will likely be implemented, that are able to deliver large volumes of hydrogen from a centralized location. The demand for hydrogen also depends on the existence of the infrastructure required to deliver and store the hydrogen. Research is ongoing in Canada [10], the US [3,50] and elsewhere on finding improved forms and ways to store and deliver hydrogen, especially over great distances and varied landscapes. The participation of fossil fuel companies could assist efforts at developing a transportation network from production facilities to distribution centers, by utilizing their expertise in large oil/gas pipeline networks.

5.1 Ecological sustainability of six categories of elements and processes

The ecological index values for 10 indicators are compared for six categories in Figure 9, where the system average for each indicator is also provided. Solid fuels exhibit low values for most of the indicators, relative to other categories and the system average, except in availability and material rate. Solid fuels have the lowest index (0.12) for ecological balance due to the use of coals, which are non-renewable energy sources. On-site fuel handling processes have higher values than other categories and the system average due to their utilitarian nature. Any system involving solid fuels requires fuel handling to operate.

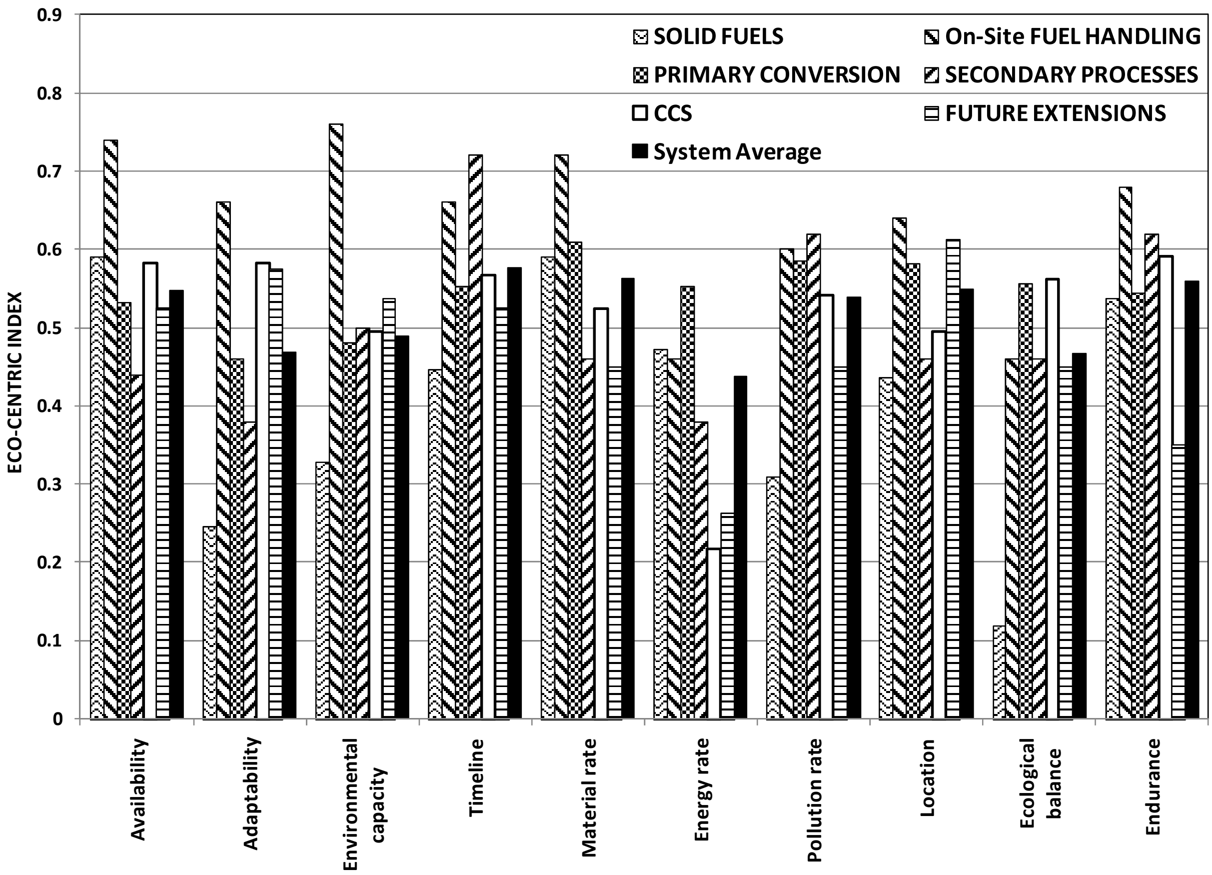

Figure 9. Comparison of eco-centric sustainability indices for the six major elements within the system, based on values for the 10 indicators discussed in section 3.1

One benefit of the integration inherent in Figure 1 is the mix of various conversion processes capable of using all type of solid fuels available in the market, thus permitting the system to operate even when some of the feedstocks shown in Figure 1 are not available on a continuous basis. For example, agricultural and forest biomass are seasonal and so may not be available throughout the year. Such supply intermittency is also observed with other renewable energy resources.

Coal is the primary solid fuel in Canada [62], and significant utilization technologies exist for it. Thus blending coal with biomass, MSW and other organic wastes allows coal supplies to be extended while improving environmental performance and facilitating effective disposal of solid wastes. The system in Figure 1 offers the flexibility to vary fuel input depending on the short- and long-term availability of various fuels at different locations.

The primary conversion processes (PCPs) in Figure 9 have an almost average performance for all the indicators. The highest value is assigned for material rate (0.61) mainly due to the gasification process, which is capable of producing almost 60% of the total hydrogen and thus involves a large-scale material rate. Adaptability scores the lowest average value (0.47) since much of the primary conversion processes are yet to adapt to the market on a large-scale and involve a large number of processes for use in the system.

The secondary conversion processes (SCPs) have index values below the system average for at lease five indicators: availability, adaptability, material rate, energy rate and location. This observation is linked to the lack of maturity of the technologies related to these processes and a consequent low market availability. These processes outperform other categories in timeline, suggesting a high chance for sustainability based on growth in the technology (as discussed in section 5.3) and in pollution rate, since harmful substances are separated by these processes. These processes are similar to on-site fuel handling in that they are required by the system to separate and purify hydrogen. All five processes are necessary for large-scale hydrogen separation since each caters to the needs of a particular primary conversion process.

Except for energy rate, the CCS options chosen for this system perform above the system average in ecological sustainability. CCS processes consume energy to perform the carbon capturing and sequestration operations. Future extensions regarding upstream fuel processing and solid waste management exhibit higher sustainability as well. Such extensions are likely to help in pollution control for emissions other than CO_2, thus leading to better ecological sustainability with time as these advanced fuel handling processes (cartridge system, upgrading, blending, solvent treatment, etc.) become more widely adopted.

Based on system average values, ecological performance is likely to improve in 1) adaptability by improving commercialization, 2) environmental capacity by adapting more stringent measures, and 3) energy rate by reducing energy wastes in operating the system.

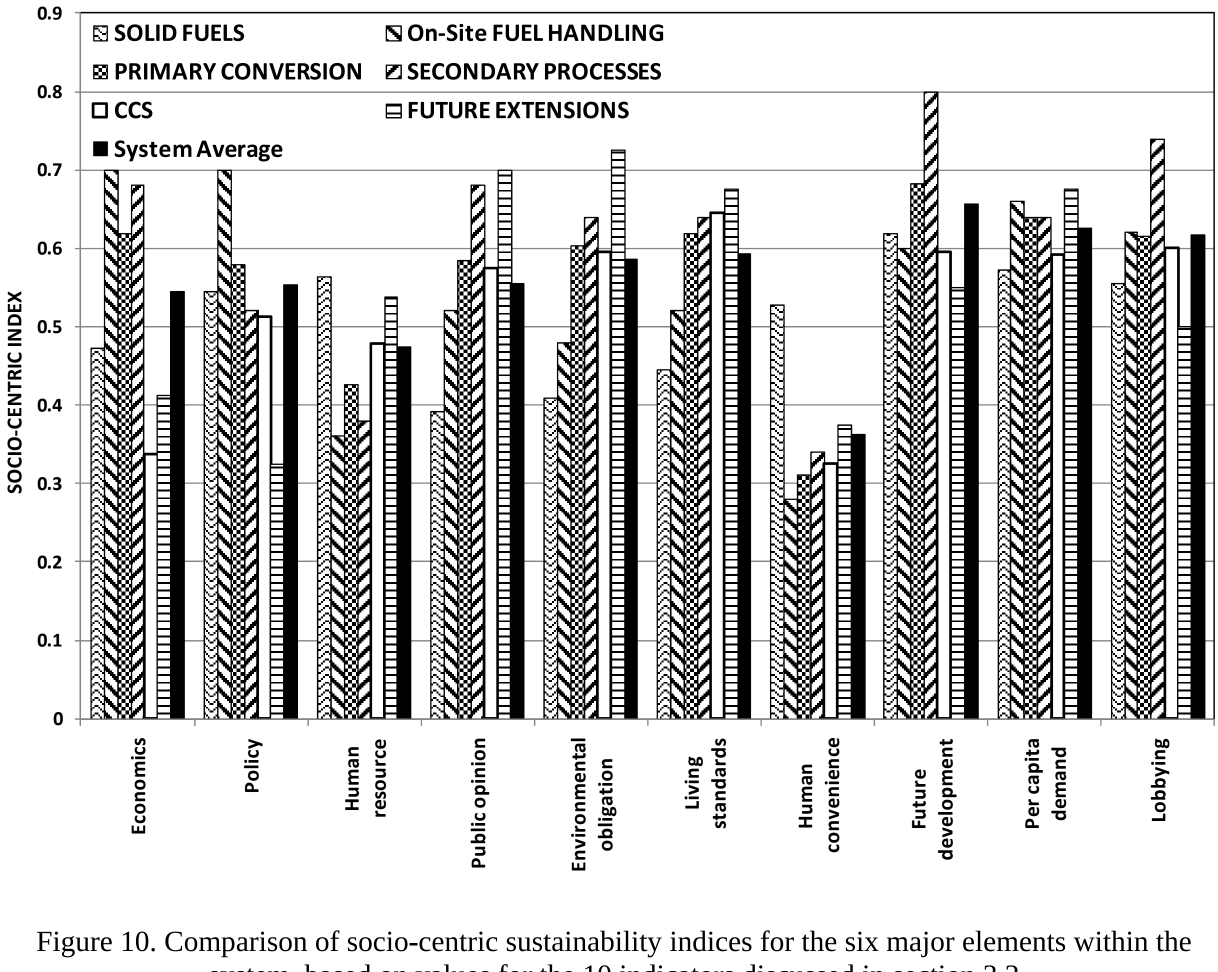

Figure 10. Comparison of socio-centric sustainability indices for the six major elements within the system, based on values for the 10 indicators discussed in section 3.2

5.2 Sociological sustainability of six categories of elements and processes

The sociological index values for 10 indicators are presented for six categories in Figure 10, along with the system average for each indicator. Solid fuels perform better in the sociological rather than ecological dimension, scoring highest (0.62) for future development. This is due to the expected growth in demand for hydrogen, which may enable large-scale use of biomass and some coals. Solid fuels exhibit a significant difference in the human convenience indicator value compared with other categories, suggesting that any additional use of solid fuels to support human convenience results in increased demand for solid fuels but an additional load on all other components in the system.

On-site fuel handling again is assigned high index values (above 0.6) for five of the sociological indicators. It scores low for human resources, since much of the operation is performed automatically. The average value of 0.42 for human resources indicates the human effort involved in designing and maintaining the automated machines. The ranking assigned for human resources may be higher during manufacturing, installation and maintenance for the on-site fuel handling system.

Except for the human resources and human convenience indicators, primary conversion processes are assigned a high value (about 0.6) for all other social indicators. These values will likely increase in time due to improved policies that provide a stable market in Canada for gasification processes and other renewable energy conversion processes such as anaerobic digestion.

The index value for human convenience will likely improve for all categories except solid fuels when broader regulations are sought by local and provincial governments for reducing waste and improving the efficiencies of electric utilities and hydrogen-based appliances in Canada [54,83].

Linkages among academia, government and industry help build the necessary human resources and skills for establishing a hydrogen economy. Activities in Canada in this regard are described in the capability report on the hydrogen and fuel cells industry in Canada for 2008 [76], which lists associated government organizations, research institutes, industries and universities involved in RD&D related to elements of the hydrogen economy. The capability report notes various collaborative hydrogen projects involving Canadian institutions and industries, some of which are discussed in the next section.

Secondary conversion processes have a high value (0.8) for the developments indicator, since most of the processes are still undergoing extensive research, increasing the probability of future developments that make the processes more sustainable.

The biggest hurdle in CCS currently [54] is the cost of capturing and sequestering CO_2. This is reflected in the economics indicator in Figure 10 for CCS which is 20% less than the system average. Improvements via RD&D and growing commercial investments in CCS suggest that improved economic performance in the near future is possible.

Future extension processes score high values (above 0.7) for public opinion and environmental obligation indicators. This suggests the importance of clean processes that also achieve good operational performance. On policy, as mentioned earlier, upstream cleaning processes are required by law in Japan but not in Canada, causing a lower index value to be observed for this indicator.

Based on system average values, the sociological performance of the system, although better than its ecological performance, requires improvements that are mostly outside the confines of the proposed system, but affect it in more than one way. In time, such improvements can be anticipated to increase the social sustainability of the system.

5.3 Technological sustainability of six categories of elements and processes

The technological index values for 10 indicators are compared for six categories as shown in Figure 11, where the system average is also provided for each indicator. Solid fuels have above system-average performance with respect to all technological indicators. These indicator values confirm the well established engineering capabilities and experience regarding solid fuels. These indicator values in turn help in improving eco- and socio-centric sustainability of solid fuels when the system is fully operational. The higher value for evolution indicates that new processes and equipment designs in the near future will almost certainly enable improved efficiencies in converting solid fuels to hydrogen.

The exergy of on-site fuel handling is the lowest value for all the indicators, suggesting that these processes do not have the capacity to transfer useful energy compared to other processes in the system. Based on the research indicator, it is evident that the incentives for research on fuel handling processes are minimal. This need should perhaps be addressed via future extension processes and research.

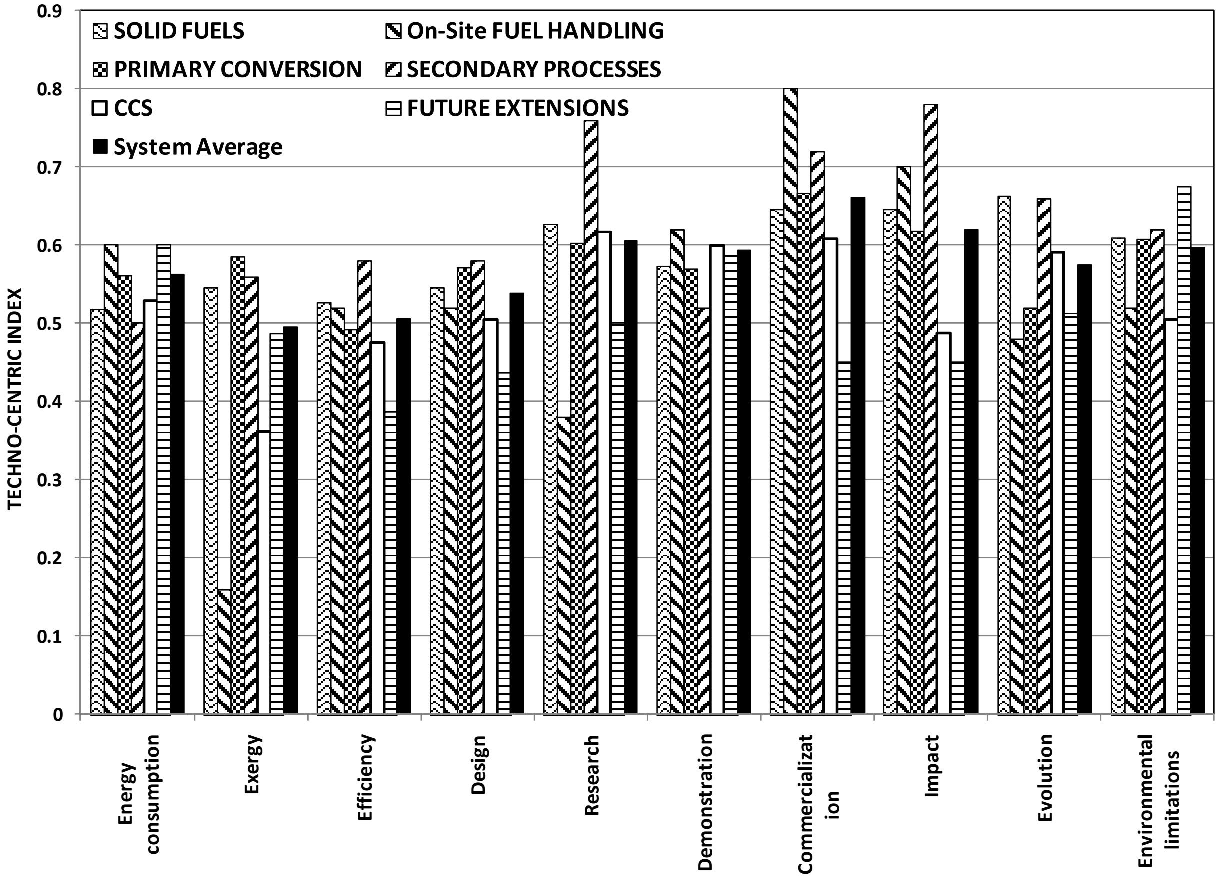

Figure 11. Comparison of techno-centric sustainability indices for the six major elements within the system, based on values for the 10 indicators discussed in section 3.3

Research on and commercialization of primary energy conversion processes are expected to improve their techno-centric sustainability. For example, biomass gasification and anaerobic digestion have good potential for electricity and hydrogen production for various reasons. These technologies have opportunities to attract investments in the near future to support their development to commercial levels, facilitated in part through various Canadian government programs [63], e.g. the Program of Energy Research and Development (PERD). Other federal government programs also fund energy-based projects including the Industry Research Assistance Program (IRAP) of the National Research Council, the Technology Partnerships Program (TPC) of Industry Canada and various grant programs of the Natural Sciences and Engineering Research Council (NSERC).

Secondary conversion processes (SCP) have high values (above 0.7) for research, commercialization and impact. There are more incentives for research and commercialization based on the distribution of energy R&D funding by the Canadian government. Presently, 20% is spent on fossil fuel-based technologies (PCP, SCP), 13% on renewable energy technologies, 22% on conservation technologies (SCP), 20% on nuclear fission/fusion, 7% on power/storage technologies and 19% on cross-cutting and other topics (SCP). Based on our previous analyses of three subsystems (gasification, combustion and chemical looping combustion) used within the proposed system in Figure 1, the financial benefit from the total R&D expenditure distribution by the Canadian government for the year 2004 [63] for the proposed system is close to 15% (3% for gasification, 2% for combustion, 4% for CCS, 3% for conservation efforts and 3% for cross-cutting R&D involving syngas and direct chemical looping development).

The technological performance of CCS processes is still lower than the system average for most of the indicators, because CO_2 capture technologies are not yet commercially implemented in Canada on a large-scale, although research is ongoing. Experiences elsewhere are accelerating CCS developments. For instance, a power plant incorporating a complete CO_2 capture and sequestration facility has been commissioned in Germany [105]. Conversion of CO_2 to algae is considered by many as a viable and sustainable process for CO_2 storage, but large-scale operations are yet to be commissioned in the world.

Future extensions have below system-average performance except for net energy consumption and environmental limitations. This is again due to the lack of such processes in the Canadian solid fuels industry.
Based on system average values, the technological performance of the system requires significant improvements to enhance its sustainability. Efficiency improvements, in particular, are essential for all components in the system. Older process designs need to be upgraded to address the challenges in ecological and sociological dimensions.

6. Conclusions

A conceptual layout of an energy conversion system has been developed for large-scale hydrogen production in Canada using solid fuels by integrating various technologies. For each of the components of the system, a qualitative analysis for the Canadian energy market of the sustainability of the system has been performed, considering three dimensions (ecological, sociological and technological) and 10 indicators for each dimension. Values for each of these indicators are generated using a 10-point scale based on a high of 1 and a low of 0, depending on the characteristic of the criteria associated with each element or process, utilizing data reported in the literature. The following inferences are derived from the current work:

- Qualitative sustainability indicators can be reasonably defined based on evaluations of system feasibility [23]. Adequate flexibility and comprehensiveness is provided through the use of 10 indicators for each of three dimensions (ecology, sociology, technology) for every process or element involved in the proposed system.
- The assessment values of indices for solid fuels suggest that it is advantageous to use coals in combination with biomass to increase their ecological and social sustainability.
- The assessments of the individual processes indicate that their sustainability is not high, indicating opportunities to improve component selection in the proposed system and to take advantage of improvements as technologies mature.
- The comparison of the indicators within each sustainability dimension for the six categories highlights the reasons for lower sustainability of certain components, and identifies processes requiring attention to improve sustainability (e.g., fuel handling and CCS).
- Biomasses have better sustainability than coals.
- Newer secondary conversion processes are essential for primary conversion of solid fuels to be sustainable, especially when using coals.
- Newly developed options for CO_2 commercial and alternate use and sequestration are likely to increase the sustainability of this technology.
- The average values for the three primary sustainability dimensions obtained through the present analysis of the proposed system are 45% for ecological sustainability, 55% for sociological sustainability and 60% for technological sustainability.

Based on this preliminary assessment, the proposed system appears moderately sustainable in a Canadian energy market for large-scale hydrogen production, but achievement of this level of sustainability, or a higher level, requires technological improvements of some of the processes, which in turn will lead to ecological and sociological enhancements.

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Appendix

Values of all the sustainability indices for every item in the system for three sustainability dimensions and for the 10 indicators are shown in Tables 1 to 3.

Table 1. Sustainability indices for every item in the system for 10 different ecological indicators

SYSTEM COMPONENTS	ECOLOGY INDICATORS										
	1	2	3	4	5	6	7	8	9	10	Total
ELEMENTS AND PROCESSES	Availability	Adaptability	Environmental capacity	Timeline	Material rate	Energy rate	Pollution rate	Location	Ecological balance	Endurance	ECO-CENTRIC
SOLID FUELS	**0.591**	**0.245**	**0.327**	**0.445**	**0.591**	**0.473**	**0.309**	**0.436**	**0.118**	**0.536**	**0.407**
COAL	**0.74**	**0.16**	**0.22**	**0.2**	**0.74**	**0.58**	**0.16**	**0.38**	**0.04**	**0.68**	**0.39**
Anthracite coal	0.5	0.1	0.2	0.1	0.7	0.8	0.1	0.2	0	0.5	0.32
Bituminous coal	0.8	0.1	0.2	0.1	0.7	0.7	0.1	0.3	0	0.8	0.38
Sub-bituminous coal	1	0.2	0.2	0.1	0.9	0.5	0.1	0.5	0	0.9	0.44
Lignite or Brown coal	0.9	0.2	0.2	0.2	0.8	0.5	0.1	0.4	0	0.8	0.41
Industrial residue	0.5	0.2	0.3	0.5	0.6	0.4	0.4	0.5	0.2	0.4	0.4
BIOMASS	**0.467**	**0.317**	**0.417**	**0.65**	**0.467**	**0.383**	**0.433**	**0.483**	**0.183**	**0.417**	**0.422**
Biomass, Forest	0.5	0.5	0.5	0.6	0.5	0.4	0.5	0.4	0.1	0.3	0.43
Biomass, Farm	0.6	0.6	0.6	0.7	0.5	0.5	0.5	0.4	0.2	0.2	0.48
Energy Crops	0.2	0.3	0.4	0.8	0.5	0.4	0.6	0.6	0.3	0.7	0.48
MSW, Sewage	0.5	0.1	0.3	0.7	0.5	0.4	0.1	0.5	0.1	0.5	0.37
MSW, Garbage	0.7	0.2	0.5	0.7	0.6	0.4	0.3	0.6	0.1	0.6	0.47
Sysem solid wastes	0.3	0.2	0.2	0.4	0.2	0.2	0.6	0.4	0.3	0.2	0.3
On-Site FUEL HANDLING	**0.74**	**0.66**	**0.76**	**0.66**	**0.72**	**0.46**	**0.6**	**0.64**	**0.46**	**0.68**	**0.638**
Storage	0.7	0.7	0.7	0.5	0.7	0.5	0.5	0.5	0.1	0.7	0.56
Drying	0.6	0.7	0.8	0.7	0.7	0.5	0.7	0.7	0.5	0.7	0.66
Crushing/Grinding	0.8	0.6	0.8	0.7	0.8	0.4	0.4	0.6	0.7	0.6	0.64
In-system transporting	0.8	0.7	0.8	0.7	0.7	0.3	0.7	0.7	0.5	0.7	0.66
Mixing of fuels, carrier gas	0.8	0.6	0.7	0.7	0.7	0.6	0.7	0.7	0.5	0.7	0.67
PRIMARY CONVERSION	**0.532**	**0.46**	**0.48**	**0.552**	**0.608**	**0.552**	**0.586**	**0.582**	**0.556**	**0.545**	**0.545**
COMMERCIAL GASIFICATION	**0.68**	**0.44**	**0.5**	**0.56**	**0.7**	**0.54**	**0.56**	**0.7**	**0.64**	**0.54**	**0.586**
Air Separation Unit	0.8	0.4	0.7	0.6	0.5	0.7	0.8	0.7	0.7	0.8	0.67
Large scale gasifier	0.5	0.3	0.4	0.7	0.9	0.5	0.6	0.7	0.6	0.7	0.59
Ash handling system	0.9	0.4	0.2	0.2	0.8	0.5	0.1	0.5	0.5	0.5	0.46
Syngas cooler	0.7	0.6	0.7	0.7	0.6	0.4	0.7	0.8	0.7	0.4	0.63
Steam generator	0.5	0.5	0.5	0.6	0.7	0.6	0.6	0.8	0.7	0.3	0.58
PLASMA GASIFICATION	**0.4**	**0.367**	**0.367**	**0.633**	**0.467**	**0.6**	**0.6**	**0.633**	**0.633**	**0.467**	**0.517**
Electric arc generator	0.2	0.5	0.3	0.5	0.3	0.8	0.7	0.6	0.5	0.4	0.48
Plasma gasifier	0.4	0.4	0.3	0.7	0.5	0.6	0.8	0.7	0.8	0.6	0.58
Slag collector	0.6	0.2	0.5	0.7	0.6	0.4	0.3	0.6	0.6	0.4	0.49
ULTRA SUPERHEATED STEAM GASIFICATION	**0.3**	**0.45**	**0.45**	**0.5**	**0.65**	**0.7**	**0.55**	**0.35**	**0.45**	**0.35**	**0.475**
Burner	0.5	0.7	0.7	0.3	0.6	0.9	0.5	0.2	0.2	0.2	0.48
USS gasifier	0.1	0.2	0.2	0.7	0.7	0.5	0.6	0.5	0.7	0.5	0.47
SUPER CRITICAL WATER GASIFICATION	**0.5**	**0.2**	**0.25**	**0.45**	**0.75**	**0.5**	**0.35**	**0.5**	**0.35**	**0.65**	**0.45**
High pressure and temperature generation	0.9	0.2	0.2	0.2	0.8	0.5	0.1	0.5	0	0.8	0.42
SCW gasifier	0.1	0.2	0.3	0.7	0.7	0.5	0.6	0.5	0.7	0.5	0.48
SOLAR THERMAL GASIFICATION	**0.4**	**0.4**	**0.75**	**0.65**	**0.35**	**0.5**	**0.65**	**0.95**	**0.6**	**0.55**	**0.58**
Solar thermal generator	0.5	0.5	0.8	0.5	0.5	0.5	0.7	1	0.6	0.7	0.63
ST gasifier	0.3	0.3	0.7	0.8	0.2	0.5	0.6	0.9	0.6	0.4	0.53
SYNGAS CLEANER	0.4	0.7	0.6	0.6	0.4	0.1	0.8	0.8	0.4	0.3	0.51
HEAT EXCHANGERS (low heat)	0.7	0.8	0.8	0.4	0.7	0.2	0.8	0.8	0.7	0.7	0.66

Table 1. Continued

SYSTEM COMPONENTS	ECOLOGY INDICATORS										
	1	2	3	4	5	6	7	8	9	10	Total
ELEMENTS AND PROCESSES	Availability	Adaptability	Environmental capacity	Timeline	Material rate	Energy rate	Pollution rate	Location	Ecological balance	Endurance	ECO-CENTRIC
DIRECT CHEMICAL LOOPING	**0.525**	**0.5**	**0.55**	**0.575**	**0.575**	**0.55**	**0.525**	**0.475**	**0.625**	**0.525**	**0.543**
Fuel reactor	0.1	0.2	0.5	0.7	0.3	0.7	0.5	0.3	0.7	0.5	0.45
Oxidation reactor	0.3	0.5	0.6	0.8	0.4	0.6	0.6	0.5	0.7	0.5	0.55
Combustion reactor	0.8	0.6	0.7	0.5	0.7	0.8	0.7	0.5	0.7	0.7	0.67
Solids handling system	0.9	0.7	0.4	0.3	0.9	0.1	0.3	0.6	0.4	0.4	0.5
ANAEROBIC DIGESTION	**0.85**	**0.75**	**0.55**	**0.55**	**0.8**	**0.3**	**0.75**	**0.55**	**0.55**	**0.6**	**0.625**
Biogas digestor	0.8	0.7	0.5	0.6	0.8	0.5	0.7	0.5	0.5	0.5	0.61
Gas treatment	0.9	0.8	0.6	0.5	0.8	0.1	0.8	0.6	0.6	0.7	0.64
PRESSURIZED FLUIDIZED BED COMBUSTION	**0.6**	**0.575**	**0.425**	**0.5**	**0.575**	**0.725**	**0.7**	**0.5**	**0.6**	**0.675**	**0.588**
PFB combustor	0.1	0.2	0.3	0.7	0.3	0.9	0.4	0.5	0.7	0.5	0.46
Heat exchanger (high heat)	0.5	0.6	0.7	0.5	0.6	0.7	0.7	0.4	0.7	0.7	0.61
Turbines	0.9	0.7	0.5	0.5	0.7	0.6	0.8	0.5	0.6	0.7	0.65
Alternators	0.9	0.8	0.2	0.3	0.7	0.7	0.9	0.6	0.4	0.8	0.63
SECONDARY PROCESSES	**0.44**	**0.38**	**0.5**	**0.72**	**0.46**	**0.38**	**0.62**	**0.46**	**0.46**	**0.62**	**0.504**
WATER-GAS SHIFT REACTOR	0.8	0.6	0.5	0.6	0.6	0.3	0.3	0.4	0.6	0.6	0.53
MEMBRANE SEPARATION	0.5	0.4	0.8	0.8	0.4	0.3	0.8	0.6	0.3	0.6	0.55
SYNGAS CHEMICAL LOOPING	0.2	0.2	0.4	0.9	0.4	0.4	0.7	0.3	0.6	0.7	0.48
ELECTROLYSER	0.2	0.2	0.2	0.8	0.3	0.4	0.8	0.5	0.3	0.7	0.44
AUTO-THERMAL REFORMER	0.5	0.5	0.6	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.52
HYDROGEN PROCESSES	**0.15**	**0.25**	**0.25**	**0.8**	**0.2**	**0.55**	**0.6**	**0.5**	**0.5**	**0.55**	**0.435**
H2 TRANSPORT	0.1	0.2	0.3	0.8	0.2	0.3	0.5	0.1	0.3	0.7	0.35
H2 STORAGE	0.2	0.3	0.2	0.8	0.2	0.8	0.7	0.9	0.7	0.4	0.52
CCS	**0.583**	**0.583**	**0.496**	**0.567**	**0.525**	**0.217**	**0.542**	**0.496**	**0.563**	**0.592**	**0.516**
CO2 COMMERCIAL USE	**0.65**	**0.6**	**0.475**	**0.5**	**0.6**	**0.2**	**0.5**	**0.625**	**0.575**	**0.55**	**0.528**
Refrigeration	0.6	0.5	0.6	0.5	0.7	0.2	0.5	0.6	0.7	0.7	0.56
Enhanced oil recovery	0.9	0.4	0.3	0.4	0.7	0.1	0.4	0.7	0.3	0.4	0.46
Working fluid	0.2	0.7	0.6	0.7	0.4	0.3	0.8	0.7	0.8	0.8	0.6
Chemical industry	0.9	0.8	0.4	0.4	0.6	0.2	0.3	0.5	0.5	0.3	0.49
CO2 UNDERGROUND STORAGE	**0.517**	**0.567**	**0.517**	**0.633**	**0.45**	**0.233**	**0.583**	**0.367**	**0.55**	**0.633**	**0.505**
Compressors	0.9	0.7	0.5	0.4	0.7	0.1	0.7	0.3	0.6	0.7	0.56
Pipeline	0.9	0.8	0.5	0.5	0.8	0.1	0.5	0.1	0.7	0.7	0.56
STORAGE GEOLOGICS	0.9	0.9	0.5	0.5	0.4	0.1	0.2	0.7	0.2	0.5	0.49
CO2 TO MINERALS	0.1	0.3	0.3	0.8	0.3	0.2	0.6	0.4	0.6	0.6	0.42
CO2 TO ALGAE	0.2	0.5	0.6	0.9	0.3	0.5	0.7	0.5	0.7	0.4	0.53
CO2 TO PLANTS	0.1	0.2	0.7	0.7	0.2	0.4	0.8	0.2	0.5	0.9	0.47
FUTURE EXTENSIONS	**0.525**	**0.575**	**0.538**	**0.525**	**0.45**	**0.263**	**0.45**	**0.613**	**0.45**	**0.35**	**0.474**
UPSTREAM FUEL CLEANING	**0.15**	**0.45**	**0.475**	**0.6**	**0.35**	**0.225**	**0.45**	**0.575**	**0.4**	**0.4**	**0.408**
Cartridge system	0	0.4	0.5	0.7	0.2	0.2	0.5	0.6	0.7	0.4	0.42
Solvent treatment	0.1	0.5	0.7	0.6	0.3	0.2	0.3	0.4	0.4	0.4	0.39
Fuel blending to reduce sulfur	0.2	0.5	0.4	0.6	0.4	0.1	0.6	0.6	0.3	0.3	0.4
Fuel upgrading	0.3	0.4	0.3	0.5	0.5	0.4	0.4	0.7	0.2	0.5	0.42
WASTE TO MATERIALS	**0.9**	**0.7**	**0.6**	**0.45**	**0.55**	**0.3**	**0.45**	**0.65**	**0.5**	**0.3**	**0.54**
Cement plant	0.9	0.7	0.5	0.5	0.5	0.4	0.6	0.8	0.7	0.4	0.6
Construction materials	0.9	0.7	0.7	0.4	0.6	0.2	0.3	0.5	0.3	0.2	0.48
System Average	0.547	0.468	0.489	0.576	0.563	0.438	0.539	0.549	0.466	0.559	0.519

Table 2. Sustainability indices for every item in the system for 10 different sociological indicators

SYSTEM COMPONENTS	SOCIOLOGY INDICATORS										
	1	2	3	4	5	6	7	8	9	10	Total
ELEMENTS AND PROCESSES	Economics	Policy	Human resource	Public opinion	Environmental obligation	Living standards	Human convenience	Future development	Per capita demand	Lobbying	SOCIO-CENTRIC
SOLID FUELS	**0.473**	**0.545**	**0.564**	**0.391**	**0.409**	**0.445**	**0.527**	**0.618**	**0.573**	**0.555**	**0.51**
COAL	**0.62**	**0.52**	**0.62**	**0.18**	**0.18**	**0.62**	**0.62**	**0.54**	**0.76**	**0.68**	**0.534**
Anthracite coal	0.6	0.5	0.7	0.1	0.1	0.7	0.7	0.5	0.8	0.8	0.55
Bituminous coal	0.6	0.5	0.7	0.1	0.1	0.7	0.7	0.5	0.8	0.8	0.55
Sub-bituminous coal	0.6	0.5	0.7	0.1	0.1	0.7	0.7	0.5	0.8	0.8	0.55
Lignite or Brown coal	0.6	0.5	0.7	0.1	0.1	0.7	0.7	0.5	0.8	0.8	0.55
Industrial residue	0.7	0.6	0.3	0.5	0.5	0.3	0.3	0.7	0.6	0.2	0.47
BIOMASS	**0.35**	**0.567**	**0.517**	**0.567**	**0.6**	**0.3**	**0.45**	**0.683**	**0.417**	**0.45**	**0.49**
Biomass, Forest	0.7	0.8	0.6	0.8	0.7	0.3	0.3	0.8	0.4	0.6	0.6
Biomass, Farm	0.8	0.8	0.6	0.8	0.7	0.4	0.4	0.8	0.4	0.6	0.63
Energy Crops	0.1	0.6	0.7	0.5	0.7	0.3	0.5	0.7	0.2	0.7	0.5
MSW, Sewage	0.2	0.5	0.4	0.6	0.6	0.3	0.5	0.7	0.5	0.3	0.46
MSW, Garbage	0.2	0.6	0.6	0.6	0.6	0.3	0.5	0.7	0.6	0.4	0.51
Sysem solid wastes	0.1	0.1	0.2	0.1	0.3	0.2	0.5	0.4	0.4	0.1	0.24
On-Site FUEL HANDLING	**0.7**	**0.7**	**0.36**	**0.52**	**0.48**	**0.52**	**0.28**	**0.6**	**0.66**	**0.62**	**0.544**
Storage	0.7	0.7	0.7	0.5	0.5	0.4	0.2	0.5	0.7	0.7	0.56
Drying	0.8	0.6	0.6	0.6	0.5	0.6	0.3	0.6	0.5	0.6	0.57
Crushing/Grinding	0.7	0.7	0.3	0.6	0.4	0.5	0.3	0.6	0.7	0.6	0.54
In-system transporting	0.7	0.8	0.1	0.5	0.4	0.5	0.3	0.6	0.6	0.5	0.5
Mixing of fuels, carrier gas	0.6	0.7	0.1	0.4	0.6	0.6	0.3	0.7	0.8	0.7	0.55
PRIMARY CONVERSION	**0.618**	**0.58**	**0.425**	**0.585**	**0.603**	**0.618**	**0.311**	**0.683**	**0.64**	**0.615**	**0.568**
COMMERCIAL GASIFICATION	**0.58**	**0.74**	**0.52**	**0.54**	**0.68**	**0.52**	**0.3**	**0.68**	**0.58**	**0.6**	**0.574**
Air Separation Unit	0.5	0.7	0.4	0.6	0.8	0.7	0.4	0.8	0.8	0.7	0.64
Large scale gasifier	0.9	0.8	0.6	0.6	0.7	0.8	0.4	0.8	0.7	0.8	0.71
Ash handling system	0.4	0.8	0.5	0.7	0.7	0.3	0.2	0.5	0.4	0.5	0.5
Syngas cooler	0.4	0.7	0.5	0.4	0.5	0.3	0.2	0.6	0.5	0.4	0.45
Steam generator	0.7	0.7	0.6	0.4	0.7	0.5	0.3	0.7	0.5	0.6	0.57
PLASMA GASIFICATION	**0.567**	**0.7**	**0.433**	**0.667**	**0.567**	**0.5**	**0.267**	**0.633**	**0.667**	**0.667**	**0.567**
Electric arc generator	0.7	0.7	0.5	0.7	0.6	0.5	0.3	0.7	0.6	0.7	0.6
Plasma gasifier	0.6	0.6	0.4	0.8	0.7	0.6	0.3	0.8	0.8	0.9	0.65
Slag collector	0.4	0.8	0.4	0.5	0.4	0.4	0.2	0.4	0.6	0.4	0.45
ULTRA SUPERHEATED STEAM GASIFICATION	**0.6**	**0.5**	**0.35**	**0.5**	**0.45**	**0.5**	**0.25**	**0.6**	**0.65**	**0.35**	**0.475**
Burner	0.6	0.7	0.4	0.7	0.3	0.4	0.2	0.7	0.6	0.4	0.5
USS gasifier	0.6	0.3	0.3	0.3	0.6	0.6	0.3	0.5	0.7	0.3	0.45
SUPER CRITICAL WATER GASIFICATION	**0.65**	**0.5**	**0.3**	**0.65**	**0.6**	**0.75**	**0.35**	**0.75**	**0.75**	**0.7**	**0.6**
High pressure and temperature generation	0.7	0.5	0.4	0.6	0.5	0.7	0.3	0.7	0.7	0.6	0.57
SCW gasifier	0.6	0.5	0.2	0.7	0.7	0.8	0.4	0.8	0.8	0.8	0.63
SOLAR THERMAL GASIFICATION	**0.6**	**0.45**	**0.45**	**0.6**	**0.7**	**0.65**	**0.35**	**0.7**	**0.65**	**0.6**	**0.575**
Solar thermal generator	0.6	0.6	0.7	0.7	0.7	0.7	0.4	0.7	0.7	0.6	0.64
ST gasifier	0.6	0.3	0.2	0.5	0.7	0.6	0.3	0.7	0.6	0.6	0.51
SYNGAS CLEANER	0.5	0.6	0.5	0.6	0.7	0.5	0.3	0.6	0.6	0.7	0.56
HEAT EXCHANGERS (low heat)	0.7	0.7	0.5	0.6	0.5	0.6	0.3	0.5	0.6	0.5	0.55

Table 2. Continued

SYSTEM COMPONENTS	SOCIOLOGY INDICATORS										
	1	2	3	4	5	6	7	8	9	10	Total
ELEMENTS AND PROCESSES	Economics	Policy	Human resource	Public opinion	Environmental obligation	Living standards	Human convenience	Future development	Per capita demand	Lobbying	SOCIO-CENTRIC
SOLID FUELS	**0.473**	**0.545**	**0.564**	**0.391**	**0.409**	**0.445**	**0.527**	**0.618**	**0.573**	**0.555**	**0.51**
DIRECT CHEMICAL LOOPING	**0.6**	**0.4**	**0.4**	**0.45**	**0.45**	**0.575**	**0.3**	**0.6**	**0.475**	**0.6**	**0.485**
Fuel reactor	0.8	0.2	0.2	0.7	0.5	0.7	0.4	0.7	0.6	0.7	0.55
Oxidation reactor	0.6	0.3	0.3	0.5	0.6	0.6	0.3	0.6	0.5	0.7	0.5
Combustion reactor	0.6	0.5	0.6	0.2	0.3	0.5	0.3	0.5	0.4	0.5	0.44
Solids handling system	0.4	0.6	0.5	0.4	0.4	0.5	0.2	0.6	0.4	0.5	0.45
ANAEROBIC DIGESTION	**0.65**	**0.65**	**0.45**	**0.8**	**0.75**	**0.75**	**0.35**	**0.8**	**0.65**	**0.75**	**0.66**
Biogas digestor	0.8	0.7	0.4	0.8	0.7	0.8	0.4	0.8	0.7	0.8	0.69
Gas treatment	0.5	0.6	0.5	0.8	0.8	0.7	0.3	0.8	0.6	0.7	0.63
PRESSURIZED FLUIDIZED BED COMBUSTION	**0.7**	**0.7**	**0.5**	**0.475**	**0.625**	**0.7**	**0.325**	**0.7**	**0.7**	**0.65**	**0.608**
PFB combustor	0.6	0.5	0.4	0.2	0.5	0.8	0.4	0.6	0.7	0.6	0.53
Heat exchanger (high heat)	0.7	0.7	0.6	0.5	0.6	0.6	0.3	0.8	0.5	0.6	0.59
Turbines	0.7	0.8	0.7	0.6	0.7	0.7	0.3	0.7	0.8	0.7	0.67
Alternators	0.8	0.8	0.3	0.6	0.7	0.7	0.3	0.7	0.8	0.7	0.64
SECONDARY PROCESSES	**0.68**	**0.52**	**0.38**	**0.68**	**0.64**	**0.64**	**0.34**	**0.8**	**0.64**	**0.74**	**0.606**
WATER-GAS SHIFT REACTOR	0.7	0.8	0.4	0.7	0.7	0.7	0.4	0.8	0.6	0.7	0.65
MEMBRANE SEPARATION	0.6	0.5	0.4	0.7	0.6	0.6	0.3	0.8	0.7	0.8	0.6
SYNGAS CHEMICAL LOOPING	0.6	0.4	0.2	0.6	0.6	0.6	0.3	0.8	0.6	0.7	0.54
ELECTROLYSER	0.9	0.4	0.5	0.8	0.8	0.7	0.4	0.9	0.8	0.9	0.71
AUTO-THERMAL REFORMER	0.6	0.5	0.4	0.6	0.5	0.6	0.3	0.7	0.5	0.6	0.53
HYDROGEN PROCESSES	**0.6**	**0.35**	**0.45**	**0.3**	**0.6**	**0.7**	**0.35**	**0.85**	**0.7**	**0.9**	**0.58**
H2 TRANSPORT	0.7	0.4	0.5	0.3	0.6	0.7	0.4	0.8	0.7	0.9	0.6
H2 STORAGE	0.5	0.3	0.4	0.3	0.6	0.7	0.3	0.9	0.7	0.9	0.56
CCS	**0.338**	**0.513**	**0.479**	**0.575**	**0.596**	**0.646**	**0.325**	**0.596**	**0.592**	**0.6**	**0.526**
CO2 COMMERCIAL USE	**0.475**	**0.525**	**0.525**	**0.6**	**0.475**	**0.625**	**0.3**	**0.625**	**0.65**	**0.65**	**0.545**
Refrigeration	0.6	0.7	0.4	0.7	0.6	0.8	0.4	0.5	0.8	0.7	0.62
Enhanced oil recovery	0.7	0.7	0.7	0.7	0.2	0.7	0.3	0.7	0.7	0.6	0.6
Working fluid	0.2	0.2	0.3	0.5	0.6	0.4	0.2	0.7	0.5	0.6	0.42
Chemical industry	0.4	0.5	0.7	0.5	0.5	0.6	0.3	0.6	0.6	0.7	0.54
CO2 UNDERGROUND STORAGE	**0.2**	**0.5**	**0.433**	**0.55**	**0.717**	**0.667**	**0.35**	**0.567**	**0.533**	**0.55**	**0.507**
Compressors	0.1	0.7	0.7	0.7	0.6	0.7	0.4	0.6	0.5	0.4	0.54
Pipeline	0.1	0.8	0.5	0.6	0.5	0.7	0.4	0.6	0.7	0.7	0.56
STORAGE GEOLOGICS	0.1	0.8	0.5	0.2	0.8	0.8	0.4	0.7	0.6	0.8	0.57
CO2 TO MINERALS	0.1	0.2	0.3	0.2	0.6	0.5	0.3	0.3	0.3	0.3	0.31
CO2 TO ALGAE	0.4	0.3	0.4	0.8	0.9	0.7	0.3	0.8	0.6	0.7	0.59
CO2 TO PLANTS	0.4	0.2	0.2	0.8	0.9	0.6	0.3	0.4	0.5	0.4	0.47
FUTURE EXTENSIONS	**0.413**	**0.325**	**0.538**	**0.7**	**0.725**	**0.675**	**0.375**	**0.55**	**0.675**	**0.5**	**0.548**
UPSTREAM FUEL CLEANING	**0.525**	**0.25**	**0.525**	**0.7**	**0.75**	**0.65**	**0.35**	**0.55**	**0.65**	**0.5**	**0.545**
Cartridge system	0.5	0.2	0.7	0.7	0.7	0.7	0.4	0.5	0.7	0.5	0.56
Solvent treatment	0.4	0.3	0.4	0.7	0.8	0.6	0.3	0.6	0.6	0.5	0.52
Fuel blending to reduce sulfur	0.6	0.3	0.4	0.7	0.8	0.7	0.4	0.6	0.6	0.5	0.56
Fuel upgrading	0.6	0.2	0.6	0.7	0.7	0.6	0.3	0.5	0.7	0.5	0.54
WASTE TO MATERIALS	**0.3**	**0.4**	**0.55**	**0.7**	**0.7**	**0.7**	**0.4**	**0.55**	**0.7**	**0.5**	**0.55**
Cement plant	0.3	0.4	0.6	0.8	0.7	0.7	0.4	0.6	0.8	0.6	0.59
Construction materials	0.3	0.4	0.5	0.6	0.7	0.7	0.4	0.5	0.6	0.4	0.51
System Average	0.545	0.553	0.474	0.555	0.586	0.592	0.362	0.657	0.625	0.616	0.557

Table 3. Sustainability indices for every item in the system for 10 different technological indicators

SYSTEM COMPONENTS	TECHNOLOGY INDICATORS										
	1	2	3	4	5	6	7	8	9	10	Total
ELEMENTS AND PROCESSES	Energy consumption	Exergy	Efficiency	Design	Research	Demonstration	Commercialization	Impact	Evolution	Environmental limitations	TECHNO-CENTRIC
SOLID FUELS	**0.518**	**0.545**	**0.527**	**0.545**	**0.627**	**0.573**	**0.645**	**0.645**	**0.664**	**0.609**	**0.59**
COAL	**0.56**	**0.7**	**0.58**	**0.6**	**0.62**	**0.58**	**0.56**	**0.68**	**0.66**	**0.56**	**0.61**
Anthracite coal	0.5	0.9	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.4	0.62
Bituminous coal	0.6	0.8	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.5	0.63
Sub-bituminous coal	0.6	0.7	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.6	0.63
Lignite or Brown coal	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.6	0.61
Industrial residue	0.6	0.5	0.5	0.6	0.7	0.5	0.4	0.6	0.5	0.7	0.56
BIOMASS	**0.483**	**0.417**	**0.483**	**0.5**	**0.633**	**0.567**	**0.717**	**0.617**	**0.667**	**0.65**	**0.573**
Biomass, Forest	0.6	0.5	0.5	0.5	0.7	0.5	0.7	0.6	0.5	0.7	0.58
Biomass, Farm	0.7	0.5	0.5	0.5	0.7	0.6	0.8	0.7	0.8	0.8	0.66
Energy Crops	0.5	0.6	0.7	0.7	0.8	0.7	0.8	0.5	0.8	0.9	0.7
MSW, Sewage	0.4	0.3	0.5	0.5	0.5	0.5	0.7	0.6	0.5	0.5	0.5
MSW, Garbage	0.4	0.4	0.5	0.5	0.6	0.6	0.8	0.7	0.8	0.8	0.61
Sysem solid wastes	0.3	0.2	0.2	0.3	0.5	0.5	0.5	0.6	0.6	0.2	0.39
On-Site FUEL HANDLING	**0.6**	**0.16**	**0.52**	**0.52**	**0.38**	**0.62**	**0.8**	**0.7**	**0.48**	**0.52**	**0.53**
Storage	0.7	0.1	0.6	0.5	0.3	0.7	0.8	0.7	0.4	0.4	0.52
Drying	0.5	0.1	0.5	0.4	0.4	0.6	0.8	0.7	0.5	0.4	0.49
Crushing/Grinding	0.5	0.1	0.7	0.6	0.5	0.5	0.9	0.7	0.5	0.6	0.56
In-system transporting	0.6	0.1	0.4	0.4	0.2	0.7	0.7	0.7	0.4	0.5	0.47
Mixing of fuels, carrier gas	0.7	0.4	0.4	0.7	0.5	0.6	0.8	0.7	0.6	0.7	0.61
PRIMARY CONVERSION	**0.561**	**0.585**	**0.492**	**0.572**	**0.603**	**0.569**	**0.666**	**0.618**	**0.52**	**0.607**	**0.579**
COMMERCIAL GASIFICATION	**0.56**	**0.44**	**0.48**	**0.54**	**0.5**	**0.56**	**0.62**	**0.64**	**0.4**	**0.6**	**0.534**
Air Separation Unit	0.3	0.3	0.3	0.7	0.6	0.6	0.7	0.8	0.5	0.7	0.55
Large scale gasifier	0.5	0.8	0.4	0.5	0.7	0.8	0.9	0.8	0.3	0.6	0.63
Ash handling system	0.5	0.2	0.5	0.4	0.3	0.3	0.4	0.4	0.2	0.8	0.4
Syngas cooler	0.7	0.2	0.6	0.6	0.5	0.5	0.5	0.6	0.4	0.5	0.51
Steam generator	0.8	0.7	0.6	0.5	0.4	0.6	0.6	0.6	0.6	0.4	0.58
PLASMA GASIFICATION	**0.4**	**0.567**	**0.533**	**0.633**	**0.5**	**0.567**	**0.633**	**0.6**	**0.433**	**0.733**	**0.56**
Electric arc generator	0.2	0.8	0.7	0.7	0.5	0.7	0.7	0.7	0.4	0.7	0.61
Plasma gasifier	0.5	0.7	0.5	0.8	0.7	0.6	0.8	0.7	0.6	0.8	0.67
Slag collector	0.5	0.2	0.4	0.4	0.3	0.4	0.4	0.4	0.3	0.7	0.4
ULTRA SUPERHEATED STEAM GASIFICATION	**0.6**	**0.65**	**0.45**	**0.45**	**0.55**	**0.55**	**0.5**	**0.65**	**0.55**	**0.55**	**0.55**
Burner	0.7	0.6	0.5	0.6	0.4	0.7	0.6	0.7	0.6	0.4	0.58
USS gasifier	0.5	0.7	0.4	0.3	0.7	0.4	0.4	0.6	0.5	0.7	0.52
SUPER CRITICAL WATER GASIFICATION	**0.5**	**0.75**	**0.5**	**0.65**	**0.65**	**0.6**	**0.75**	**0.75**	**0.6**	**0.7**	**0.645**
High pressure and temperature generation	0.5	0.8	0.5	0.6	0.7	0.6	0.7	0.7	0.5	0.5	0.61
SCW gasifier	0.5	0.7	0.5	0.7	0.6	0.6	0.8	0.8	0.7	0.9	0.68
SOLAR THERMAL GASIFICATION	**0.65**	**0.55**	**0.5**	**0.55**	**0.75**	**0.45**	**0.75**	**0.55**	**0.6**	**0.55**	**0.59**
Solar thermal generator	0.8	0.6	0.6	0.6	0.8	0.4	0.8	0.6	0.7	0.6	0.65
ST gasifier	0.5	0.5	0.4	0.5	0.7	0.5	0.7	0.5	0.5	0.5	0.53
SYNGAS CLEANER	0.6	0.3	0.4	0.6	0.5	0.6	0.6	0.5	0.6	0.8	0.55
HEAT EXCHANGERS (low heat)	0.7	0.4	0.6	0.4	0.5	0.7	0.6	0.4	0.5	0.5	0.53

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Table 3. Continued

SYSTEM COMPONENTS	TECHNOLOGY INDICATORS										
	1	2	3	4	5	6	7	8	9	10	Total
ELEMENTS AND PROCESSES	Energy consumption	Exergy availability	Efficiency	Design	Research	Demonstration	Commercialization	Impact	Evolution	Environmental limitations	TECHNO-CENTRIC
DIRECT CHEMICAL LOOPING	**0.5**	**0.575**	**0.5**	**0.45**	**0.575**	**0.45**	**0.575**	**0.65**	**0.575**	**0.55**	**0.54**
Fuel reactor	0.3	0.6	0.5	0.4	0.7	0.4	0.7	0.8	0.7	0.5	0.56
Oxidation reactor	0.5	0.7	0.6	0.5	0.6	0.3	0.6	0.9	0.7	0.7	0.61
Combustion reactor	0.7	0.8	0.4	0.6	0.5	0.6	0.6	0.5	0.6	0.6	0.59
Solids handling system	0.5	0.2	0.5	0.3	0.5	0.5	0.4	0.4	0.3	0.4	0.4
ANAEROBIC DIGESTION	**0.5**	**0.5**	**0.35**	**0.6**	**0.7**	**0.65**	**0.7**	**0.6**	**0.5**	**0.75**	**0.585**
Biogas digestor	0.6	0.7	0.2	0.6	0.7	0.7	0.8	0.7	0.6	0.7	0.63
Gas treatment	0.4	0.3	0.5	0.6	0.7	0.6	0.6	0.5	0.4	0.8	0.54
PRESSURIZED FLUIDIZED BED COMBUSTION	**0.775**	**0.65**	**0.625**	**0.7**	**0.6**	**0.725**	**0.8**	**0.5**	**0.5**	**0.425**	**0.63**
PFB combustor	0.6	0.8	0.4	0.6	0.6	0.6	0.7	0.4	0.6	0.4	0.57
Heat exchanger (high heat)	0.8	0.7	0.6	0.7	0.6	0.7	0.8	0.6	0.5	0.5	0.65
Turbines	0.8	0.5	0.8	0.7	0.6	0.8	0.8	0.5	0.5	0.4	0.64
Alternators	0.9	0.6	0.7	0.8	0.6	0.8	0.9	0.5	0.4	0.4	0.66
SECONDARY PROCESSES	**0.5**	**0.56**	**0.58**	**0.58**	**0.76**	**0.52**	**0.72**	**0.78**	**0.66**	**0.62**	**0.628**
WATER-GAS SHIFT REACTOR	0.4	0.4	0.6	0.5	0.7	0.6	0.7	0.8	0.7	0.5	0.59
MEMBRANE SEPARATION	0.6	0.3	0.7	0.7	0.8	0.4	0.9	0.8	0.8	0.8	0.68
SYNGAS CHEMICAL LOOPING	0.4	0.6	0.5	0.6	0.8	0.3	0.6	0.8	0.6	0.5	0.57
ELECTROLYSER	0.5	0.8	0.7	0.6	0.9	0.7	0.9	1	0.7	0.8	0.76
AUTO-THERMAL REFORMER	0.6	0.7	0.4	0.5	0.6	0.6	0.5	0.5	0.5	0.5	0.54
HYDROGEN PROCESSES	**0.5**	**0.55**	**0.35**	**0.25**	**0.8**	**0.65**	**0.8**	**0.95**	**0.7**	**0.65**	**0.62**
H2 TRANSPORT	0.3	0.2	0.3	0.2	0.7	0.5	0.7	0.9	0.6	0.7	0.51
H2 STORAGE	0.7	0.9	0.4	0.3	0.9	0.8	0.9	1	0.8	0.6	0.73
CCS	**0.529**	**0.363**	**0.475**	**0.504**	**0.617**	**0.6**	**0.608**	**0.488**	**0.592**	**0.504**	**0.528**
CO2 COMMERCIAL USE	**0.475**	**0.375**	**0.45**	**0.525**	**0.55**	**0.5**	**0.6**	**0.475**	**0.55**	**0.475**	**0.498**
Refrigeration	0.4	0.3	0.4	0.6	0.5	0.4	0.6	0.4	0.5	0.6	0.47
Enhanced oil recovery	0.3	0.3	0.5	0.6	0.6	0.6	0.8	0.6	0.5	0.4	0.52
Working fluid	0.7	0.5	0.5	0.4	0.4	0.5	0.4	0.5	0.6	0.7	0.52
Chemical industry	0.5	0.4	0.4	0.5	0.7	0.5	0.6	0.4	0.6	0.2	0.48
CO2 UNDERGROUND STORAGE	**0.583**	**0.35**	**0.5**	**0.483**	**0.683**	**0.7**	**0.617**	**0.5**	**0.633**	**0.533**	**0.558**
Compressors	0.4	0.7	0.8	0.7	0.6	0.6	0.8	0.6	0.5	0.6	0.63
Pipeline	0.6	0.2	0.4	0.6	0.5	0.5	0.6	0.5	0.5	0.5	0.49
STORAGE GEOLOGICS	0.7	0.1	0.5	0.3	0.8	0.7	0.9	0.4	0.6	0.4	0.54
CO2 TO MINERALS	0.5	0.4	0.5	0.3	0.6	0.7	0.3	0.4	0.6	0.4	0.47
CO2 TO ALGAE	0.6	0.4	0.6	0.7	0.9	0.8	0.5	0.6	0.8	0.8	0.67
CO2 TO PLANTS	0.7	0.3	0.2	0.3	0.7	0.9	0.6	0.5	0.8	0.5	0.55
FUTURE EXTENSIONS	**0.6**	**0.488**	**0.388**	**0.438**	**0.5**	**0.588**	**0.45**	**0.45**	**0.513**	**0.675**	**0.509**
UPSTREAM FUEL CLEANING	**0.6**	**0.575**	**0.475**	**0.525**	**0.6**	**0.575**	**0.45**	**0.5**	**0.525**	**0.6**	**0.543**
Cartridge system	0.6	0.7	0.5	0.4	0.6	0.5	0.5	0.5	0.6	0.5	0.54
Solvent treatment	0.6	0.4	0.4	0.5	0.6	0.5	0.6	0.5	0.4	0.6	0.51
Fuel blending to reduce sulfur	0.6	0.4	0.4	0.6	0.5	0.6	0.4	0.5	0.4	0.8	0.52
Fuel upgrading	0.6	0.8	0.6	0.6	0.7	0.7	0.3	0.5	0.7	0.5	0.6
WASTE TO MATERIALS	**0.6**	**0.4**	**0.3**	**0.35**	**0.4**	**0.6**	**0.45**	**0.4**	**0.5**	**0.75**	**0.475**
Cement plant	0.7	0.5	0.4	0.5	0.5	0.8	0.6	0.4	0.5	0.7	0.56
Construction materials	0.5	0.3	0.2	0.2	0.3	0.4	0.3	0.4	0.5	0.8	0.39
System Average	0.563	0.496	0.506	0.538	0.605	0.593	0.66	0.62	0.575	0.598	0.575

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