Next generation biorefineries will solve the food, biofuels, and environmental trilemma in the energy–food–water nexus

Y.-H Percival Zhang¹,²,³,⁴

¹Biological Systems Engineering Department, Virginia Tech, 304 Seitz Hall, Blacksburg, Virginia, 24061
²Institute for Critical Technology and Applied Science (ICTAS), Virginia Tech, Blacksburg, Virginia, 24061
³Gate Fuels Inc., 2200 Kraft Drive, Suites 1200B, Blacksburg, Virginia, 24060
⁴Cell-Free Bioinnovations Inc., Blacksburg, Virginia, 24060

Abstract

The future roles of biomass and carbohydrate for meeting needs of food/feed, renewable materials, and transportation fuels (biofuels) remain controversial due to numerous issues, such as increasing food and feed needs, constraints of natural resources (land, water, phosphate, biomass, etc.), and limitations of natural photosynthesis, as well as competing energy conversion pathways and technologies. The goal of this opinion article is to clarify the future roles of biomass and biorefineries using quantitative data other than adjective words. In most scenarios, human beings could have enough biomass resource from plant photosynthesis for meeting the three goals at the same time: feeding 9 billion people, providing renewable materials, and producing transportation biofuels that could replace nearly all fossil fuel-based liquid fuels used in the land transportation in 2050. Land transport means will pass through transitions from internal combustion engines plus liquid fuels, to hybrid systems, to hydrogen fuel cell vehicles (FCVs), while battery electric vehicles (BEVs) could play a minor role. Next generation biorefineries based on artificial photosynthesis featuring ultra-high energy efficiency and low-water consumption could produce a large amount of carbohydrate and/or other biocommodities from hydrogen/electricity and CO₂. In conclusion, it is time to develop next generation biorefineries, which will efficiently utilize nonfood biomass for the coproduction of multiple products from biofuels, biochemicals, to food/feed, and even store electricity/hydrogen by fixing CO₂ to carbon-containing chemicals and biofuels. Next generation biorefineries will address the food, biofuels, and environment trilemma at the same time.

Introduction

Modern civilization is the product of incessant utilization of natural resources on large scales: fossil fuels (e.g., oil, gas, and coal), renewable energy (e.g., biomass, wind, and solar), water, and land [1–4]. Among finite fossil fuels, cheap crude oil will run out first within next several decades [5, 6]. Therefore, it is a great scientific and engineering challenge to replace cheap oil with something that can be produced from renewable resources [7]. Feeding the world population from 7 billion now to 9 billion in 2050 [8] poses another challenge by considering constraints of natural resources – limited farming land supplies and emerging water crisis [9–11]. In addition, food security is closely related to issues of food distribution, geopolitical stability, cost volatility, and functional nutrition [12], which are not discussed here. Although water is renewable, the collective fresh water demand of human beings could exceed foreseen supply by ca. 40% in 2030 [13]. This water shortage could escalate food prices, disrupt energy production, constrict trade, create refugees, and undermine authority [13].

Biomass is defined as biological materials. Nearly, all biomass (i.e., plant, animal, and microbial) originates...
from CO₂ fixation by natural photosynthesis. It has played important roles in human societies: (i) cereals from cultivated grains and grass from managed pastures are food and feed sources, respectively, accounting for approximately 2.0% of terrestrial net primary production (NPP); (ii) approximately, 2.3% of terrestrial biomass is directly burned for cooking and heating, especially in developing countries, or eventually converted to biogas as a secondary energy carrier; (iii) wood and other cellulosic materials accounting for approximately 1% of terrestrial NPP is used as construction materials and to make paper and renewable polymers (e.g., cellophane, rayon); and (iv) approximately, 0.2% of terrestrial NPP (e.g., corn kernels, sugarcane, and vegetable oil) is converted to liquid transportation biofuels in first generation biorefineries. It is important to retain biomass’ irreplaceable roles as food/feed, construction materials, papers, and renewable polymers and then investigate whether there will be enough extra biomass resource to meet other needs.

Biofuels are defined as a secondary energy used in the transport sector, which is derived mainly from biomass [14–16]. First-generation biofuels include ethanol produced from sugarcane and starch-rich biomass (e.g., corn kernels, wheat, and aged cereals) and biodiesel produced from vegetable oils and animal fats. First-generation biofuels produced from food source receive severe criticisms because their impacts on the transportation fuels are minimal mainly due to limited feedstock supplies and their production has a minimum effect on a reduction of net greenhouse gas emissions [17, 18]. For example, it is estimated that replacing 5% of energy consumption through first generation biofuels could double water withdrawals for agriculture [13]. Clearly, the global production of first generation biofuels is not sustainable and is endangering current agricultural systems. Second-generation biofuels are produced mainly from nonfood biomass, such as cellulosic ethanol, butanol, fatty acid ethyl esters, methane, hydrogen, methanol, dimethyl ether, Fischer-Tropsch diesel, and bioelectricity [4, 19]. Because there are so many different energy conversion pathways (i.e., biological, thermochemical, and their hybrids) to converting nonfood biomass to a large variety of potential biofuels, which biofuels will become short-, middle- and long-term transportation fuels is a matter of vigorous debate [4, 19, 20]. Additionally, the future role of biomass in the nexus of energy, water, and food is not clear.

This article provides much-needed clarity on the desirability and feasibility of next generation biorefineries that will utilize nonfood biomass resource and/or even fix CO₂ through artificial photosynthesis. Such biorefineries will meet needs of food/feed and biofuels while not endangering water security and maintaining biodiversity.

**Appraisal facts**

It is necessary to provide some quantitative data pertaining to energy production and consumption, resource availability, and constraints of natural resources and bio-systems before the potential impacts of next generation biorefineries are predicted.

**Energy status quo**

Generally speaking, energy demands determine energy production and conversion [4]. Typical energy systems are comprised of three basic components: primary (natural) energy sources, their conversion to secondary energies (i.e., #1 and #2 intermediates), and end applications from food/feed to energy to materials. In the past human societies, the simplest systems utilized one or two of energy sources (e.g., biomass) through few kinds of inefficient energy conversion for meeting basic needs – food/feed and cooking/heating. In contrast, modern societies can utilize numerous primary sources (e.g., fossil fuels, insolation, nuclear, and wind energy), convert them to a few energy carriers (e.g., electricity, hydrogen, and liquid fuels) with enhanced energy conversion efficiencies, and apply them in a myriad of ways to power complex high-energy societies [4, 21]. Figure 1 presents future pathways between basic needs and renewable primary energy without fossil fuels. In it, the needs of food/feed and renewable materials (i.e., paper, timber, and polymers) will have to be met by biomass and/or carbon-containing compounds made from artificial photosynthesis, while the energy needs (e.g., transport, heat/cooling) could be met through a variety of energy intermediates from numerous primary energy sources.

![Figure 1. Human needs are and will be met from sustainable primary energies through numerous intermediates. Solid lines mean practical conversions; dash lines mean hypothetical conversions in the future.](image-url)
Table 1. The world energy production and some major applications.

| Name                  | Power (TW) | Percentage | References |
|-----------------------|------------|------------|------------|
| Fossil fuels          | 13.10      | 72.02%     | [22]       |
| Oil                   | 5.22       | 28.70%     | [22]       |
| Gas                   | 3.61       | 19.85%     | [22]       |
| Coal                  | 4.27       | 23.47%     | [22]       |
| Nuclear               | 0.29       | 1.61%      | [22]       |
| Renewables            | 4.80       | 26.39%     |            |
| Biomass - heating     | 1.50       | 8.25%      | [29]       |
| Food/Feed1            | 1.33       | 7.31%      | [11]       |
| Wood2                 | 1.28       | 6.60%      | [100]      |
| Hydroelectricity      | 0.39       | 2.15%      | [22]       |
| New renewables3       | 0.30       | 1.64%      | [22, 32]   |
| Total                 | 18.19      | 100.01%    |            |

12.5 billion tons of cereals and grass [11].
23.5 billion cubic meters [100].
3Including solar cells, biofuels, wind, and geothermal energy.

Table 1 presents status quo of the world’s energy production, where food/feed and wood consumption are included, because they are major energy consumption sections and their production greatly competes with the production of other energy for requiring water and land. Fossil fuels including oil, gas, and coal account for approximately 72% of the world’s energy consumption. Crude oil is the largest primary energy and its major usage is transportation fuels – gasoline, middle distillates (e.g., diesel), jet fuels, and fuel oil, accounting for more than 60% of oil consumption [22]. Renewable energy resources accounts for approximately 26% of the world’s energy consumption. Biomass is the largest utilized renewable energy source: heating fuel (i.e., 1.50 TW), 2.5 billion tons of food (i.e., 1.33 TW), and 3.5 billion cubic meters of wood (i.e., 1.28 TW). In all, the world’s energy consumption is estimated to be 18.2 TW. This value is approximately 20% higher than the widely used value of 15 TW in the literature [23] because the smaller value does include neither food/feed nor wood consumption for materials.

Transportation fuels

Mobility reflects the level of civilization [4, 24, 25]. Human societies have passed through two transportation revolutions: from animal forces to external combustion engines to internal combustion engines (ICES) [2, 16, 19, 26]. Affluent countries consume more transportation energy per capita than developing countries. For example, the global transport sector consumes approximately 20% of the energy produced (Table 1), and the transport sector in the United States consumes approximately 28% of the total energy [16].

Vehicles running on land constitute the largest type of transportation energy consumption. They have some special requirements, such as high energy storage capacity in a small container, high power output, affordable fuel, affordable vehicle, low costs for rebuilding the relevant infrastructure, fast charging or refilling of the fuel, and high safety [16]. Such strict requirements lead to the outcome – that ICEs along with high-energy density liquid fuels are the dominant transport means [4]. However, the depletion of crude oil, rising prices of crude oil, the accumulation of greenhouse gases, and concerns of national energy security are motivating the development of new sustainable transport means.

Food and feed

Food is fundamental to human well-being and development [27]. Henry Kissinger, a former US Secretary of State, said “control oil and you control nations; control food and you control the people.” In 5000 years of Chinese history, a lack of food supplies frequently resulted in dynasty shifts. Increasing food production is believed to effectively alleviate global food insecurity and stabilize societies.

The global energy market in terms of calories is approximately 13 times the food and feed market (Table 1). The ratios of the overall energy to food/feed are higher than 20 or even 40 in affluent countries and lower than 10 in developing countries [1, 28]. Therefore, the production of food/feed could be not as important in developed countries as in developing countries from a perspective of energy production and consumption.

Food and feed production is water-intensive. A simple rule of thumb is that it takes a half to one L of water to grow one calorie of cereals, depending on cultivation conditions and cereal types [13]. For example, the production of one kilogram of wheat requires the use of 1300 kg of water on average. Meat production, on average, requires about ten times the water per calorie than that of plants. For example, 10,000–20,000 kg of water are required to produce 1 kg of beef [13].

Currently, human beings consume approximately 2.5 billion tons of dry weight of harvested crops include approximately 2.3 billion tons of cereals (e.g., rice, wheat, and corn kernels) and grass from managed pastures [28]. Cultivated plants used for food and feed account for approximately 1.5% of the world’s NPP, which is calculated from the data of Tables 1 and 2.

Growing population and continuous consumption growth per capita mean that the global demand for food/feed will increase by 50–100% in 2050 [9, 11]. Food
security is inextricably linked to growing pressure on land, water, and energy resources [10]. Recent events of drought, large-scale land investments, and high energy prices underscore the world’s food security. In addition, issues of food distribution, geopolitical stability, cost volatility, and functional nutrition could lead to hunger in some areas [12].

Natural resources

Renewable energy

Three major types of renewable energies are solar radiation, geothermal energy, and tidal energy. The six transformations of solar radiation are wind, wind-generated ocean waves, ocean currents, hydro energy, thermal difference between the ocean’s surface and deep water, and biomass [29, 30]. Not all renewable energy sources can be utilized. For example, very low energy concentration (nonpoint) energies in terms of W/m², such as ocean thermal differences, currents, and biomass in ocean, are difficult to collect and utilize economically [4]. Additionally, some fraction of energy resources cannot be utilized economically. For example, it is estimated that only 2.2% of wind energy resource could be utilized in the future (Table 2). Similarly, most biomass on lands cannot be economically collected and utilized due to high collection and transportation costs and/or environmental concerns. Approximately, 12.3% of biomass could be utilized, nearly double to current biomass consumption (i.e., 4.11 TW) [19, 31]. This data suggest that biomass resource may not be as large as expected.

Solar radiation is the largest renewable energy source (Table 2). Approximately, 170 petawatt (PW, $10^{15}$ W) radiation reaches Earth and approximately 30% is immediately reflected and scattered in the upper atmosphere [24, 32]. Once the radiation enters the atmosphere, a complex series of reflections and absorptions take place. Thirty-one petawatt insolation is converted to thermal energy in the atmosphere and the remaining solar radiation at the surface is approximately 87 PW [24, 32], approximately 5000 times of the world’s energy consumption. Of 87 PW surface radiation, 38 PW becomes thermal energy in the land and ocean, 41 PW contributes to evaporating water, and 5 PW diffuse radiation is reflected off the surface and escapes into space, and a very small fraction goes to photosynthesis [32]. Earth’s land surface, ocean, and atmosphere absorb solar radiation, and this raises their temperature and evaporates water, causing atmospheric circulation or convection. When the wet air reaches a high altitude where the temperature is low, water vapor condenses into clouds and then to rain/snow onto the Earth’s surface, completing the water cycle. The latent heat of water condensation amplifies convection, producing atmospheric phenomena, such as wind, hurricanes, and cyclones [24, 32].

Water

Although it is renewable, water has no substitutes or alternative. Agriculture consumes approximately 3100 billion tons of water, accounting for 71% of fresh water withdrawals today for the production of approximately 2.5 billion tons of food [13]. Industrial withdrawals and domestic withdrawals account for 16% and 14%, respectively [13]. The changes in population growth from 7 billion to 8 billion in the next two decades, economic growth and urbanization, accompanied with increased food demand per capita will intensify global water consumption. It is expected that the collective demand of the humans for water will exceed foreseen supply by about 40% in 2030 [13]. Compared to availability of land and energy consumed, water is the biggest limiting factor in the world’s ability to feed a growing population [13].

Land

The total arable land on Earth is 4.2 billion hectares [28]. Approximately, a third of arable land is being cultivated [28]. In reality, the potential to convert the remaining land is limited because most uncultivated land plays vital ecological roles [28]. Half of potential arable land is available only in seven countries (i.e., Brazil, Democratic Republic of the Congo, Angola, Sudan, Argentina, Columbia, and Bolivia) [28]. On the other extreme, South Asia and the Near East/North Africa have no spare land [13]. Overall, the world’s net amount of arable land could expand an additional seventy million hectares, being 5% [13]. Also, aggressive expansion of agricultural lands from forest and grassland will impair biodiversity and release a large amount of new CO₂ emissions [18, 33].

### Table 2. The renewable energy sources and their potentials.

| Renewable energy | Resource (TW) [1, 24, 29, 32] | Resource potential (TW) | Utilization percentage |
|------------------|-------------------------------|-------------------------|------------------------|
| Surface insolation | 87,000 | 50.7 | 0.06% |
| Wind | 870 | 19.1 | 2.2% |
| Wave/Tide | 63.7 | 1.6 | 2.5% |
| Geothermal energy | 32 | 15.9 | 49.6% |
| Hydroelectric energy | 7.2 | 1.0 | 13.9% |
| Photosynthesis | 90 | | |
| Land | 65 | 7.99 | 12.3% |
| Ocean | 25 | | |

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The issues of energy, water, and land used for the food production have been interwoven ranging from ensuring access to services, to environmental impacts, to price volatility [34]. Systematic analysis and paradigm-shifting solutions are highly required to address challenges of the energy–food–water nexus.

**Natural photosynthesis**

Natural photosynthesis comprises a set of photochemical and redox reactions, called the “light reactions” and a sequence of enzymatic synthesis reactions, called “light-independent reactions” [17, 35–37]. In the light reactions, photosynthetic pigments (e.g., chlorophyll molecules) absorb approximately 47% of the light of the sun called “photosynthetic active radiation,” but do not include green light, UV, and IR irradiation [37, 38]. The adsorbed energy is transferred to the reaction centers where the primary charge separation and transmembrane transport of electrons occurs. Subsequent electron- and proton-transfer reactions lead to the synthesis of ATP from ADP and inorganic phosphate and NADPH synthesis from NADP⁺. In theory, eight photons are required to reduce two molecules of NADP⁺ to NADPH. In reality, approximately 9.4 photons are consumed, that is, 11.8% of the energy of sunlight can be converted to the form of NADPH, which is close to the efficiency limit of the photosynthetic production of biohydrogen under optimal insolation [17, 39]. Light reactions have the highest photosynthesis efficiency at relatively low light intensities. The efficiency is saturated at 20% of full sunlight and decreases greatly at high light intensities. In addition, high light intensities lead to photo damage of a central protein subunit of the photosynthetic apparatus. The energy efficiency of light-independent reactions are limited by (i) low chemical synthesis efficiency of the enzyme RuBisCO for taking up low-concentration CO₂ from air and removing 2-phosphoglycolate; (ii) availability of sufficient amounts of water that is not met during much of the day and of fertilizers, and (iii) respiration of living organisms [17, 38, 40]. Light reactions operate on very short time scales from femtoseconds to milliseconds, while light-independent reactions operate over a timespan of seconds to hours [35, 36]. As a result, natural plant photosynthesis has low theoretical energy efficiencies from solar energy to chemical energy of 4.6 and 6.0% for C₃ and C₄ plants, respectively [38]. Although global efficiency of plant photosynthesis is 0.2%, the global primary biomass production is approximately five times the world’s energy consumption (Tables 1 and 2).

Best energy efficiencies for well-fertilized and well-watered crops are between 2% and 3% [28]. In the past decades mainly due to the green revolution, yields of crops have increased by approximately three times [11]. Now global means of corn, wheat, and rice are 3.5, 2.0, and 2.5 ton/ha, respectively [28]. The highest corn, wheat, and rice harvest records are 22, 15.2, and 15.2 ton/ha, but such high crop productivities are achieved at the costs of high energy inputs, such as fertilizers, insecticides, and water [28]. As crop yields increases, the ratio of photosynthetic energy captured to energy spent on crop cultivation has decreased [41]. For example, ca. 50% fertilizers or even 70% used for cultivating high-yield crops in the United States and China cannot be utilized, resulting in serious nonpoint water pollution from farmland [42]. Therefore, it raises a challenge: how to increase crop yields while simultaneously decreasing energy consumption and utilizing natural resources, such as water and phosphate, more efficiently.

**Key questions to clarify**

The following addresses four key questions pertaining to the energy–food–water nexus and clarifies the roles of next generation biorefineries in the sustainability revolution.

**Could we have enough biomass to feed the world?**

There is no doubt that the production of food is more important than the production of energy and materials. Prior to the green revolution, the production of food was the first priority for human beings for several thousand years. For example, the former Soviet Union and United States investigated the production of single-cell proteins from crude oil. When the food supplies are abundant, the prices of food decrease greatly and the prices of crude oil soars, the production of liquid transportation fuels (i.e., ethanol and biodiesel) from food sources is in practice, especially the United States and Brazil. However, it is discouraged or even prohibited to expand the production capacity of first generation biofuels in most countries, such as China and the European Union, mainly due to the concern of food security.

How to meet increasing food needs is becoming a global challenge [10, 11, 43, 44]. Because the production of 2.5 billion tons of food has utilized ~30% arable lands and ~70% freshwater withdrawals, it is difficult to greatly increase agricultural lands and increase water withdrawals. Therefore, a group of scientists [9] suggests a variety of solutions to address food security: (i) closing yield gaps on underperforming lands, (ii) increasing agricultural resource efficiency, and (iii) increasing food delivery by shifting diets and reducing food waste, while halting agricultural land expansion. For example, several studies find...
that about one-third to one half of food is never consumed [45, 46]. For example, developing countries usually lose more than 40% of food postharvest or during processing, while industrialized countries often lose more than 40% of food at the retail or consumer levels [45]. On the other hand, some plant biologists, big plant companies, and policy makers promoted the genetically modified (GM) crops as a future solution [47]. However, long-term impacts of GM cereals on human health are not clear and their wide application is in heated debates [47–51].

Here, a paradigm-shifting solution is proposed – enzymatic biotransformation of cellulose to synthetic starch in next generation cellulosic biorefineries [52]. Via biomass fractionation [53], a variety of multiple products could be produced from major lignocellulosic components: cellulose, hemicellulose, and lignin (Fig. 2). I demonstrate simultaneous enzymatic biotransformation and fermentation (SEBF) that can transform cellulosic materials to starch, ethanol, and single-cell protein in one vessel in the presence of cascade enzymes isolated from bacteria, fungus, and plant sources, and a typical ethanol-producing yeast. Our data showed that up to 30% of the anhydromannose units in cellulose were converted to synthetic starch; the remaining units were hydrolyzed to glucose suitable for yeast fermentation that can produce ethanol. This cellulose to starch biotransformation could be scaled up by increasing the stability of two key enzymes – cellbiose phosphorylase and starch phosphorylase because this process does not involve any labile coenzymes (e.g., CoA and NAD(P)); no glucose is wasted; neither energy nor costly reagents is added. The stability of both cellbiose phosphorylase [54] and starch phosphorylase [55] can be enhanced greatly by protein engineering. Also, starch production from cellulose mediated by enzymes rather than GM organisms may avoid potential negative impacts of GM cereals and prevent bioethics debate.

Cellulose resource is approximately 40 times the starch produced by cultivated crops. Every ton of cereals harvested is usually accompanied by the production of at least two tons of cellulose-rich crop residues, most of which are not utilized [56]. In addition to the use of agricultural and forest residues (e.g., straws, corn stover, and wood dust), growing dedicated bioenergy crops could greatly increase biomass availability. Dedicated bioenergy crops usually have much higher productivities (e.g., approximately 40–80 ton/ha/y [57–59]), have much higher water utilization efficiency, require less energy-related inputs, such as fertilizers, pesticides, seeds, and harvesting, and herbicides, tolerate harsher environments, and could not require annual seedling, compared to cultivated starch-rich crops. Dedicated bioenergy crops can grow on low-quality arable land.

The Department of Energy (DOE) of the United States has summarized three distinct goals associated with potential bioenergy crops: (i) maximizing the total amount of biomass produced per hectare per year, (ii) producing sustainable biomass with minimal inputs (e.g., pesticides, fertilizers, seeds, and harvesting), and (iii) maximizing the amount of biofuels that can be produced per unit of biomass [60]. A yield of ca. 50 dry tons per hectare per year may be considered as a reasonable target in an area with adequate rainfall and good soil [60], which is about 15–25 times average yields of cultivated cereals. In addition to well-studies bioenergy crops, such as switchgrass, poplar, and Miscanthus [59, 61, 62], this study recommends two new promising bioenergy plants – bamboo and common reed. Although both of them have been cultivated and harvested in some areas, they are often ignored by most. Bamboos are giant woody, tree-like, perennial evergreen grasses [58]. They have been cultivated in East Asia and South East Asia [63]. Phyllostachys pubescens (Moso bamboo) grows in a subtropical monsoon climate but it can withstand as low as −20°C in winter. It can be cultivated in marginal lands, such as mountain valley, foot of mountain, and gentle slope. The bamboo productivity is highly dependent on soil, water, and climate conditions. The highest average yearly biomass productivity during 10-year plantation is approximately 76 tons of dry culms/ha/y, which can be easily collected [64]. Phragmites australis (common reed) is a widespread perennial grass that grows in wetlands or near inland water ways [57]. Although it is harvested for thatched roofs, ropes, baskets, and pulping feedstock, the common reed is more typically considered an invasive weed due to its vigorous growth and difficulty of eradication. Common reed could be used as a bioenergy crept
due to three unique features: (i) high biomass productivity (e.g., ca. 45–71 tons/ha/y), (ii) low inputs needed for planting, such as water, fertilizers, and pesticides, and (iii) removal of phosphorus- and nitrogen-containing pollutants in water ways [57].

Intensive irrigation for cultivating dedicated bioenergy crops could not be recommended. Since it consumes approximately three and one orders of magnitude water based on energy content more than the production of oil from traditional oil drilling and advanced oil recovery, respectively [13], the production of biomass is believed to increase usage of freshwater [65, 66]. This issue has raised concerns about the increase in water stress, particularly in countries that are already facing water shortage [67]. Therefore, cultivating future dedicated bioenergy crops must take into account water consumption.

In a word, the cost-effective transformation of nonfood cellulose to starch could not only revolutionize agriculture by promoting the cultivation of plants chosen for rapid growth rather than those optimized for starch production [68–70] but also could maintain biodiversity and minimize agriculture’s environmental footprint [71]. Also, wide implementation of cellulosic biorefineries would decrease postharvest food loss, especially for developing countries, so to increase overall food/feed availability [72].

**What powertrain and fuel will become the dominant transport means in the future?**

A number of scenarios (Fig. 1) can and could bridge between renewable primary energy and transportation energy demand through four powertrain systems: (i) ICEs and/or hybrid electric vehicles (HEVs) that burn liquid biofuels and compressed methane [19, 73], (ii) BEVs that run on electricity stored in rechargeable batteries, where electricity can be generated from sun radiation, tide, geothermal, wind, and nuclear energy [74], (iii) hydrogen FCVs that run on stored hydrogen through proton exchange membrane (PEM) fuel cells and electric motor [73], and (iv) sugar fuel cell vehicles (SFCVs) that run on stored sugar as a high-density hydrogen carrier based on FCVs [25]. Powertrain systems for vehicles must meet all of the following criteria: high energy storage capacity in a small container, high power output, economically competitive fuel, affordable vehicle, fast charging or refilling of the fuel, and high safety [16].

Table 3 compares the gravimetric energy densities of liquid fuels, stored hydrogen, rechargeable batteries, and capacitors, as well as kinetic energy output densities on wheels through different powertrain systems. The energy storage densities in a decreasing order are diesel, gasoline, butanol, ethanol, methanol, sugar, stored hydrogen, rechargeable batteries, and capacitors. Liquid gasoline and diesel plus their respective ICEs have kinetic energy output densities of 6.50 and 8.32 MJ/kg, respectively. When ICE’s energy efficiencies are increased through hybrid electric systems, HEV-gas, and HEV-diesel can drive farther. Conventional hydrogen storage means have lower energy storage densities from 5.0 to 9.3 MJ/kg or even

| Name                                      | Gravimetric energy density (MJ/kg) | Kinetic energy output (MJ/kg) | Powertrain (efficiency, %) |
|-------------------------------------------|------------------------------------|-------------------------------|---------------------------|
| H$_2$ without container                   | 143                                | NA                           | NA                        |
| Diesel                                    | 46.2                               | 8.32                          | ICE-diesel (18%)           |
|                                           |                                    | 17.09                         | HEV-diesel (37%)           |
| Gasoline                                  | 46.4                               | 6.50                          | ICE-gas (14%)              |
|                                           |                                    | 14.38                         | HEV-gas (31%)              |
| Butanol                                   | 36.6                               | 5.12                          | ICE-gas (14%)              |
|                                           |                                    | 11.35                         | HEV-gas (31%)              |
| Ethanol                                   | 30                                 | 4.20                          | ICE-gas (14%)              |
|                                           |                                    | 9.30                          | HEV-gas (31%)              |
|                                           |                                    | 11.10                         | HEV-diesel (37%)           |
| Methanol                                  | 19.7                               | 6.90                          | DMFC (35%)                 |
| Starch/Cellulose                          | 17.0                               | 8.16                          | Sugar-H$_2$-PEMFC/Motor (48%)|
| 8% H$_2$ mass including container         | 11.4                               | 5.13                          | PEMFC/Motor (45%)          |
| Cryo-compressed H$_2$ including container | 9.3                                | 4.19                          | PEMFC/Motor (45%)          |
| Compressed H$_2$ (700 bars) including container | 6.0                             | 2.70                          | PEMFC/Motor (45%)          |
| 4% H$_2$ mass including container         | 5.7                                | 2.57                          | PEMFC/Motor (45%)          |
| Compressed H$_2$ (350 bars) including container | 5.0                             | 2.25                          | PEMFC/Motor (45%)          |
| Lithium ion rechargeable battery          | 0.56                               | 0.381                         | BEV (68%)                  |
| NiMnH rechargeable battery                | 0.36                               | 0.245                         | BEV (68%)                  |
| Lead acid rechargeable battery            | 0.14                               | 0.095                         | BEV (68%)                  |
| Ultra-capacitor                           | 0.02                               | 0.016                         | Motor (80%)                |
| Super-capacitor                           | 0.01                               | 0.008                         | Motor (80%)                |

DMFC: direct methanol fuel cell; PEMFC: proton exchange membrane fuel cell.
lower, resulting in shorter driving distance of FCVs compared to vehicles based on ICEs if the same weight fuel tank is used. Therefore, the DOE strongly encourages to develop novel high-density hydrogen storage means and provides the H-prize cash award [16]. Rechargeable batteries have at least one order magnitude lower energy storage densities than liquid fuels and stored hydrogen (Table 3). As a result, BEVs have very short driving distances. The energy densities of capacitors are very low, limiting its application in the transport sector.

Battery electric vehicles will not be a dominant future transport means. For example, the International Energy Agency and several studies predict that BEVs will play a minor role in the future [74, 75]. Rechargeable lithium (Li) batteries have energy densities of approximately 150 Wh/kg (i.e., 0.56 MJ/kg), resulting in very short driving distances for BEVs [76, 77]. If the energy densities of lithium batteries were increased by 5–10-fold [78, 79], other issues, such as safety, recharging time, and lifetime, could still prohibit their wide use in personal vehicles. In reality, future energy densities of rechargeable lithium batteries are expected to increase by twofold in next decades [76, 77] rather than 5–10 times by considering the configuration of Li batteries and its combustion energy (i.e., 43.1 MJ/kg lithium) [4]. Although developing lithium-air batteries are expected to have very high energy densities but the regeneration of lithium oxidize to lithium by electricity is energy intensive. Therefore, metal-air batteries are not suitable in the transport sector.

In addition to low energy densities of Li batteries, BEVs have other weaknesses. First, the recharging cycles and lifetime of high-density lithium batteries is approximately 1000 time and 2–3 years, respectively. Both are much shorter than requirement of the major car components lasting at least 10 years. (Think of lithium ion batteries in cellphones and laptops.) Second, lithium ion batteries are still costly for vehicles although its production costs could be decreased by several-fold. It is not realistic to believe that battery costs would be drastically decreased following Moore’s Law because it is impossible to exponentially both decrease material consumption in batteries and increase battery performance according to the basic physical limits of materials. Third, Li batteries require a long recharging time. Although ultra-fast charging batteries have been developed [80], these capacitor-like batteries are made at the cost of decreasing energy storage densities [81]. Fourth, a huge infrastructure investment could be needed to upgrade the electrical grid, install sockets for fast recharge, and build power stations [21]. Fifth, disposing and recycling a large number of used rechargeable batteries could be another environmental challenge [21]. Sixth, the energy density loss rates of rechargeable batteries depend on temperature; for example, standard loss rates per year are 6% at 0°C, 20% at 25°C, and 35% at 40°C [21]. Seventh, whether there is enough low-cost lithium for BEVs is not a certain thing. Goodenough, a pioneer of lithium batteries, pointed out that the principal challenges facing the development of rechargeable batteries for BEVs are cost, safety, energy density (voltage x capacity), rate of charge/discharge, and service life [82]. Due to BEVs’ unique features such as cleanliness and quietness, BEVs will still be popular in some special markets, for example, in golf courts. In a word, a complete switch to all battery electric cars is utterly unrealistic [21] by considering the above problems and the likelihood that better competing technologies will appear and mature.

This study suggests another paradigm-shifting solution for the future vehicles – SFCVs. Based on FCVs, carbohydrate (shorthand, CH2O) is suggested to be a high-density hydrogen carrier so that its use could address hydrogen storage, distribution, and safety issues [40, 83–85]. In the hypothetical SFCV, an on-board biotransformer containing numerous thermoenzymes and (biomimetic) coenzymes that can achieve the reaction of CH2O + H2O → 2H2 + CO2 [86, 87]. Because enzymes are 100% selective, work under moderate reaction conditions, and generate highly pure hydrogen, carbohydrates have a gravimetric density of 8.33 H2 mass% for the carbohydrate/water slurry [16, 25]. During the past several years, we have increased enzymatic hydrogen generation rates to approximately 160 mmole H2/L/h by nearly 800-fold (in preparation for publication). We anticipate to increase reaction rates by another 30-fold within next several years so that the on-board biotransformer will be small enough to store in a SFCV [16, 40].

In a word, HEVs based on ICEs are believed to be a short- and middle-term solution before FCVs [73]. SFCVs could be a good solution to address the problems of FCVs from hydrogen production, storage, distribution, infrastructure, and safety. SFCVs could have several advantages over BEVs: much higher energy storage densities, faster refilling rates, better safety, and less environmental burdens [19, 40].

**Could we have enough extra biomass source to drive vehicles and feed the world?**

As shown in Table 1, two irreplaceable applications of biomass resource are food/feed (1.33 TW) and wood for materials (1.28 TW). Compared to all terrestrial biomass resource (65 TW), the current biomass utilization efficiency is 6.32% and it is expected that biomass utilization efficiency will be increased to up to 12.3% [31]. This value is also partially supported by the DOE and USUA’s a billion ton report [88]. Two liquid fuels used for land
transportation are gasoline (1.2 TW) and middle distillates (1.79 TW). Since the global average ICE-gas and ICE-diesel have fuel-to-wheel efficiencies of approximately 14% and 23%, respectively [19], the global kinetic energy output on wheels is 0.58 TW.

When we increase biomass utilization efficiency from 6.32% now to 12.3% in 2050, this study provides quantitative predictions for the worst, best, and most likely scenarios for the year 2050 based on different assumptions. In the worst scenarios, food/feed needs, wood consumption, and biomass for burning could increase by 100%, 50%, and 50%, respectively. At the same time, total biomass resource could be constant. Therefore, the remaining biomass source that could be collected and utilized will be 1.17 TW. The land transportation energy in terms of kinetic energy could increase to 0.85 TW from 0.58 TW based on an annual growth rate of 1%.

In the best scenarios, food/feed needs and wood consumption could increase by 50% and 20%, respectively. Slow growth in wood consumption could be attributed to less use of papers in affluent countries and better recycling. Biomass for burning could be decreased to half due to an increase in burning efficiency in developing countries [24]. At the same time, total biomass resource could increase to 94.9 TW at an annual growth rate of 1% due to (i) rising CO2 levels in the atmosphere that fertilizes plant productivity [19, 38] and (ii) dedicated high-yield bioenergy crops [88]. Therefore, the biomass resource will be 7.52 TW. The land transportation energy in terms of kinetic energy could increase to 0.70 TW based on an annual growth rate of 0.7%.

The last uncertainty is the biomass-to-wheel (BTW) efficiency of future land transport means. The worst scenario is based on current ICE-gas (ethanol) system (BTW = 7%), while the best could be SFCVs (BTW = 27%). Several transitional powertrains could be HEV-gas (BTW = 20.7%), HEV-diesel (BTW = 24.8%), and FCV (BTW = 22%). In the 2050 market, it is likely that the transport sector could constitute different transport means so that an average BTW efficiencies could range from 11% to 20%.

Table 4 presents the analysis for the future biomass and biofuels roles. In the worst scenarios, biomass could play a significant role in replacing approximately 10–25% transportation fuel need. On the contrast, in the best scenarios, biomass could be sufficient to meet all land trans-

| Table 4. Scenarios of the roles of biomass for the production of food/feed, wood, heating, and land transportation fuels in 2050. |
|---------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| **Worst 2050**                  | **Best 2050**  | **Highly possible 2050** |
| **Name**                        | Power (TW)    | Assumption    | Name            | Power (TW)    | Assumption    | Name            | Power (TW)    | Assumption    |
| Food/Feed                       | 2.66          | 100% gain     | Food/Feed       | 2.00          | 50% gain      | Food/Feed       | 2.26          | 70% gain      |
| Food/Feed crops                 | 2.66          | 100% gain     | Food/Feed crops | 1.86          | 40% gain      | Food/Feed crops | 1.66          | 35% gain in crop |
| New food/Feed                   | 0.00          | NA            | New food/Feed   | 0.13          |                | New food/Feed   | 0.60          |                |
| Wood                            | 1.92          | 50% gain      | Wood            | 1.54          | 20% gain      | Wood            | 1.66          | 30% gain      |
| Burning                         | 2.25          | 50% gain      | Burning         | 0.75          | 50% decrease  | Burning         | 1.50          | No change     |
| Total land biomass              | 65            | No change     | Total land biomass | 94.87       | 1% gain/year  | Total biomass resource | 78.56       | 0.5% gain/year |
| Available biomass               | 1.17          | 12.3% biomass use | Available biomass | 7.52          | 12.3% biomass use | Available biomass | 4.84          | 12.3% biomass use |
| Land kinetic energy             | 0.85          | 1% gain/year  | Land kinetic energy | 0.70          | 0.5% gain/year | Land transportation use | 0.76          | 0.7% gain/year |
| **Scenario**                    | **Land fuel replacement** | **BTW** | **Land fuel replacement** | **BTW** | **Land fuel replacement** | **BTW** | **Land fuel replacement** | **BTW** |
| S1: ICE-gas (ethanol)           | 9.6%          | BTW = 7%      | S4: HEV-gas (ethanol) | 156%         | BTW = 15%     | S7: ICE/HEV-gas (ethanol) | 54.6%        | BTW = 11%    |
| S2: HEV-gas (ethanol)           | 20.7%         | BTW = 15%     | S5: FCV         | 229%          | BTW = 22%     | S8: HEV-gas (ethanol) | 74.4%        | BTW = 15%    |
| S3: HEV-diesel (ethanol)        | 24.8%         | BTW = 18%     | S6: SFCV        | 280%          | BTW = 27%     | S9: SFCV/SFC/HEV | 99.2%        | BTW = 20%    |

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transportation energy need plus a large surplus. In the most likely scenarios, biofuels made from biomass could replace at least 50% to nearly 100% land transportation fuel need. The above analysis suggests that (i) we must increase powertrain system efficiency so to decrease biomass consumption, (ii) we must develop next generation biorefineries because it not only produce biofuels but also could produce food/feed and biochemicals, and (iii) we must utilize agricultural and forest residuals and then grow dedicated water-saving bioenergy crops by spatial segregation of food/feed and energy-producing areas by continuing producing food on established and productive agricultural land while growing dedicated energy crops on marginal land [89].

Could we surpass natural photosynthesis?

This study suggests developing next generation biorefineries by integrating high-efficiency solar cells or other electricity-generating systems, water electrolysis, with biological CO$_2$ fixation mediated by cell-free synthetic cascade enzymes (Fig. 3). This cell-free biosystem is believed to work based on the design principles of synthetic biology, knowledge in the literature, and thermodynamics analysis [40, 90]. This hypothetical system could have numerous advantages. First, solar cells have much broader light adsorption spectrum and higher efficiencies than plant pigments. Also, the efficiency of solar cells, unlike plants, does not change in response to insolation variation. Also, it is easy to concentrate nonpoint insolation to a point energy – electricity. Second, hydrogen generated by water electrolysis at daytime can be stored for a few hours so that it can be consumed at a constant synthesis rate for the biological CO$_2$ fixation process at night. Therefore, it is easy to regulate and match changed-rate electricity generation and constant-rate biosynthesis process. Third, the products of artificial photosynthesis are carefully chosen: water-insoluble amylose, volatile alcohols, or water-insoluble fatty alcohols. So the product separation costs could be minimal. Fourth, ultra-high energy efficiency from hydrogen or electricity and CO$_2$ to chemical energy could be achieved, much better than natural processes mediated by living organisms that dissipate energy by respiration [91–93]. Table 5 presents the comparison between natural photosynthesis and artificial photosynthesis. Validation experiments and practical application of these systems will require worldwide collaborative efforts from biologists, chemists, electrochemists, and engineers [90] (Note: It is important to fix high concentration CO$_2$ generated from power stations rather than to capture atmospheric CO$_2$ because the latter requires extremely high energy inputs, resulting in economical infeasibility [94]).

In a word, next generation biorefineries based on artificial photosynthesis would not only bridge the current and future primary energy utilization systems aimed at facilitating electricity and hydrogen storage but also address such sustainability challenges such as renewable biofuel and chemical production, CO$_2$ utilization, and fresh water conservation [90]. Its large-scale implementation would foster the switch from fossil fuel-based resources to renewable bioresources.

Recommendations

First, the development of next generation biorefineries based on nonfood biomass is a must rather than an option because they will produce a variety of products that cannot be substituted by other renewable resources,
such as transportation fuels, biochemicals, and food/feed. With respect to biomass fractionating and biorefining technologies, the production of multiple products in next generation biorefineries will be of importance to their economic viability because natural biomass feedstock contains multiple components (Fig. 2). With respect to feedstock, we need start utilizing the ready agricultural and forest residues before we grow dedicated bioenergy crops on a large scale. Also, it is strongly recommended not to change current agricultural lands used for food/feed production to the production of bioenergy crops, which could lead to food shortage. With respect to biofuels, biofuels must be produced from sugars through anaerobic fermentation because a fraction of sugar in aerobic fermentation is wasted, resulting in low energy efficiencies [20, 95]. The failure of Amyris’s and LS9’s efforts on biofuels production is a good example – hopeless aerobic fermentation.

Second, it is extremely important to develop more energy efficiency powertrain systems from ICEs to HEVs to FCVs to SFCVs. Increasing energy utilization efficiency is a megatrend for human societies [2, 4, 24]. Higher energy efficiency means less primary energy consumption and lower environmental footprints.

Third, it is important to develop next generation biorefineries based on artificial photosynthesis that can produce carbon-containing compounds from CO₂ and H₂/energy. Large-scale implementation of artificial photosynthesis would address such sustainability challenges as electricity and hydrogen storage, CO₂ utilization, fresh water conservation, and maintenance of a small closed ecosystem for human survival in emergency situations [90].

Fourth, to address food security, it is recommended (i) not to increase the production capacity of first generation biofuels, and (ii) not to grow GM cereals as the future food source. Human beings will have enough food/feed without GMs cereals by increasing traditional crop productivity, decreasing food waste, enhancing food distribution, and producing synthetic starch from nonfood cellulosic resource, and even producing amylose through artificial photosynthesis. Additionally, potential negative impacts of GM cereals on human health should not be underestimated because systematic long-term studies are not available and may not be conductive. For example, negative effects of saturated fat are recently realized after its long utilization [96, 97]. Cotton seed oil was once used to replace vegetable oil as food. After years, it was found that the use of cottonseed oil resulted in low fertility in males [98]. Similarly, chronic negative effects of tobacco were realized in 1960s after its use for several thousand years. Therefore, it is not necessary to take risk in consuming GM cereals but its benefits to food security are not irreplaceable.
In a word, biomass sugar isolated from nonfood biomass and/or produced from artificial photosynthesis could play an irreplaceable role in the sustainability revolution by providing food/feed, renewable materials, and transportation biofuels in the future.

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Conflict of Interest

The authors declare competing financial interests. The enzymatic sugar-to-hydrogen technology is protected by the US patent 8211681. The enzymatic transformation of non-food biomass to edible starch is under protection of the US patent 8111681. The enzymatic sugar-to-hydrogen technology is protected by the US patent 8211681. The enzymatic sugar-to-hydrogen technology is protected by the US patent 8211681. The enzymatic sugar-to-hydrogen technology is protected by the US patent 8211681.

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