**WORLD SOLAR GUIDE** 1

**Part 8**

**Policies and Strategies**

**for the Implementation of Global Renewable Energy**

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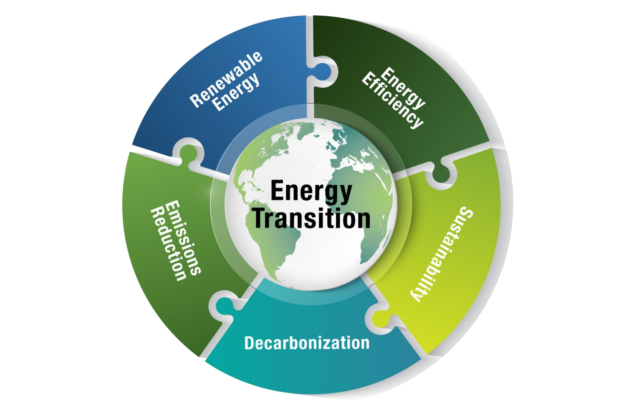


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**World Solar Guide**

**Part 8**

**Policies and Strategies**

**for the Implementation of Global Renewable Energy**

1. Introduction

Fossil fuels were produced from plant and animal matter in the earth’s crust beginning approximately **300 million years** ago.

The Industrial Revolution started around 1750 based, primarily, on deposits of coal. The period of fossil energy using coal, oil, and natural gas will likely end around 2050, either physically or economically, a time span of only **300 years**. Thus, the ratio of “supply-demand” periods is one-million-to-one.

This revolution has been one of the world’s most transformative forces in recorded history. Its transition to renewable sources will be no less so.

The earth is now faced with the task of rapidly transforming its energy supplies from fossil fuels to renewable sources in an optimistically projected period of only **30 years,** from 2020 to 2050.

UN negotiations to achieve the goal of limited the atmospheric temperature increase to 1.5 C to 2.0 C began in 1998 and culminated with the Paris Accords in 2015, a period of 27 years (nearly30 years). During this period, the earth’s temperature increased nearly 1.0 C, leaving the acceptable increase to only 0.5 C to 1.0 C at 2050. Nationally Determined Contributions (NDCs) of most countries were submitted, but many remain inadequate.

Ironically, all the necessary concepts to produce renewable energy were known **200 years** ago. For example, the (solar) photovoltaic effect, electrolysis, and fuel-cell principles were demonstrated in the early 1800’s, as were many electrical concepts. Also, an early model for global warming was developed by Svante Arrhenius in 1897.

In addition, electrical devices, including vehicles were produced in the late 1800’s. However, the discovery of oil at Titusville, Pennsylvania in 1870, followed by subsequent discoveries around the world bypassed, many electrical applications.

The chemical element, *carbon*, is essential for biosphere processes and all organic reactions. Yet, cries for the “decarbonization of the economy” echo throughout government buildings.

Carbon, of course, is connected to oxygen when fossil fuels are burned or oxidized. Without CO2, the earth’s temperature would be sub-zero. The current problem with CO2 is its exponentially increasing atmospheric excesses.

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*Carbon dioxide* is a molecule in which the vibrations between its two oxygen atoms and the carbon atom are quantized, that is, they occur at specific frequencies which occur in the frequency range or, in the case of electromagnetic waves, in the wavelength range of the earth’s average black-body infrared radiation temperature of about 20 C or 293 K. This green-house gas has increased from about 300 to 400 ppm (0.03% - 0.04%) during the past 170 years, and this increase is strongly correlated with the atmosphere’s increasing temperature. *Methane,* CH4, is 30 times as effective in absorbing the earth’s IR radiation because this molecule has more quantized vibrational modes than CO2. Methane, the largest component of natural gas, is converted to CO2 and H2O upon oxidation (CH4 + 2O2 🡪 CO2 + 2H2O).

In the twentieth century, the world endured two world wars, each lasting more than four years, and a decade-long economic depression. In the 1930’s General Dwight Eisenhower served as an aid to General Douglas MacArthur and soon became known for his logistics skills. Because of this talent, among others, he was selected by General George Marshall to work with British Prime Minister, Winston Churchill, in planning the D-Day invasion of Normandy which took place on June 6, 1944. Elected President of the United States in 1952, Eisenhower proposed an interstate-highway program for the US which was constructed during the 1950’s and 1960’s. President Kennedy, in 1961, stated the ambitious goal of landing a man on the moon by the end of the decade, an effort which required contributions from 20,000 companies. It is these types of programs which should be considered as models for the transition of fossil fuels to renewables over a period of the next 30 years in the US.

The transition will require parallel-track strategies consisting of emission-mitigation and energy plans together with economic sustainability measures to minimize dislocations as determined by individual countries. It can already be seen that while some countries are well on their way to achieving their goals, other are falling behind and may not produce meaningful results by 2050.

Encouraging developments are currently in progress. Several municipalities, states, provinces, and countries are installing renewable systems at increased rates relative to their previous investments. In addition, utility companies are now investing more new capital in renewable sources than in fossil fuels. Manufacturers of solar panels, electrolyzers, and fuel cells are expanding their production capabilities in accordance with the growing demand for green hydrogen. International markets for hydrogen are under development.

**Parts 1, 2, and 3** of the Guide have presented some of the scientific and technical aspects of renewable energy. Many features are well known and have been implemented in several forms. Continued R&D is crucial to ascertain the fundamentals of processes such as catalysis in electrolyzers and fuel cells. Another difficult task will be the development of policies and strategies which will result in a reasonably smooth transition from fossil fuels to renewables during the period of 2020 to 2050. Many points in **Part 8** have been referenced in earlier segments of this guide. It is suggested that readers can apply these policy and strategy concepts to the evaluation of their needs for renewable sources, particularly solar energy, by linearly scaling the guide’s results in **Part 2** to distributive, grid, municipal, regional, or national levels.

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It should be noted that, in addition to the 2030 gap, none on the models from Climate Action Tracker [1] predict a “net-zero” emissions scenario by 2050 in Figure 1. Only the 1.5C model shows “net-zero,” and this projection occurs around 2085. A target gap of 2.7 C or 4.9 F is expected by the year 2030. It is emphasized that the “net-zero” scenario is different from the “100% renewable energy” scenario as the former is possible with a significant amount of fossil fuels.

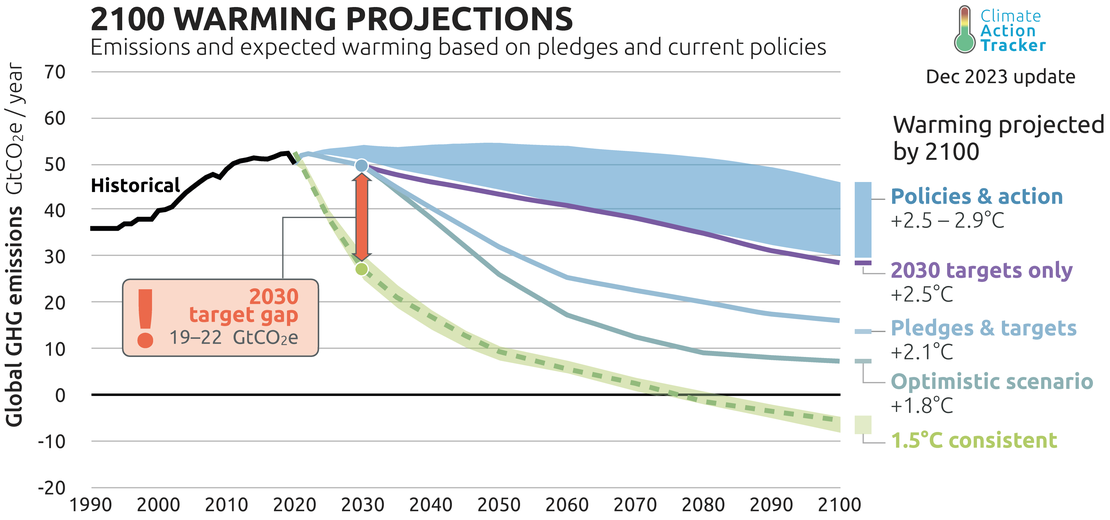


Figure 1. Global warming projections. Image from [1].

**Part 2** of this guide analyzed the world’s four largest energy regions. Among these regions, China, the USA, Europe-E5 (UK, Germany, France, Spain, and Italy), and India, only four European countries, UK, Germany, France, and Spain show a positive index. These regions account for most of the world’s energy consumption, and the E5 region uses about 7% of this energy as seen in Table 1.

Table 1.

World Energy Use

China 23%

USA 17

Europe-E5 7

India 6

Total 54

The terms, “Policies” and “Strategies” are often used somewhat ambiguously and interchangeably in their applications. They are normally applied in government, business, economic, and finance circles. In the context of global warming and mitigation measures, for example, the statements of the IPCC and the Paris Agreement, the policy of minimizing global warming used includes a strategy of replacing fossil fuels with renewable energy sources.

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2. Policy Statement

The policy statement in this Guide is based on the results of **Parts 1-7**. Policies are statements of values. The following components of a renewable-energy policy statement illustrate these values.

2.1 Environment

The IPCC presented its Paris Accord Agreement in 2015. Nationally Determined Contributions (NDCs) were requested from participating countries to limit the atmospheric temperature increase to the range of 1.5 C to 2.0 C. Compliance with this requirement is currently incomplete. Later, “Net-Zero by 2050” pathways were developed which would decrease the current level of global CO2 emissions, 40 Gt per year, to zero (1 Gt = 1billion metric tonnes).

2.2 Energy Security

In addition to environment concerns, countries wish to have secure energy supplies. Whereas fossil fuels are distributed unevenly and, in many cases depleted, solar radiation is more uniformly dispersed around the globe, albeit with higher irradiance values nearer the equator as shown in several **Part 2** maps. Countries should also consider export-import options of commodities such as photovoltaic power and hydrogen as components of their security needs.

2.3 Economic Viability and Benefits

The transition from fossil fuels to renewable must be implemented over a period, currently considered to be about 30 years, in such a way as to minimize economic dislocations due to excessive inflation, job loss, and negative GDP. This transition will require detailed plans at many levels (local, regional, national), across all sectors (electric, industrial, transportation, building), and among many entities (private, public, educational). Sustainable environmental policies and renewable-energy development should result in economic benefits. These benefits, which have been projected to increase because of the transition are often measured by employment and GDP growth.

2.4 Societal Improvements

Societies should expect improved health and lower medical costs from reduced pollution.

2.5 Land Use

Renewable energy sources will require large amounts of land, often within countries of high population densities and terrain restrictions. Careful analyses of land-use requirements should be carried out before the installation of resources.

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3. World Solar Guide System and Other Systems

The renewable energy system described in in **Part 2** of the World Solar Guide in the production of utility-scale electric power, is based on solar photovoltaic panels which provide power to water electrolyzers producing green hydrogen during the six-hour “day-time” period. The stored hydrogen is then directed to fuel cells with a connection to a utility-scale electric grid in the 18-hour “night-time” period. The electrolyzers also produce hydrogen which is delivered to industrial, transportation, and building sectors. Citations in **Part 2** have found that 90% of all energy sources must be electrified for the purpose of meeting the net-zero CO2 emissions standard by 2050. These systems are shown in **Part 2** with a general schematic diagram in Figure 9.1 and Tables 9.1, 9.2, 14.6, and 14.7.

While solar energy will be the largest portion of renewables, other sources such as wind, hydro, and biomass will also contribute to the mix. Thus, the PV-EL-FC system described in this Guide may be excessive by a factor of two. Nevertheless, its features will serve as upper limits to the required resources of power, water, storage, and land. In addition, the analyses in Part 3 have provided estimates of material limits such as silver as used in photovoltaic devices and the platinum group of metals for electrolyzer and fuel cell electrodes. Substitute materials were considered.

Readers are encouraged to evaluate alternative systems as discussed in **Part 1** and **Part 2**, to determine the mix of renewable sources which is most suitable to their applications. However, the strategies discussed below will concentrate on the PV-EL-FC system described in this guide.

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4. Strategies

“Pathways” or “actions” can be considered as “strategies. Strategies can also be considered as means of achieving goals. These goals are usually long-term in nature. Short-term goals or objectives are achieved through “tactical” measures. The IEA’s “Pathway to Net-Zero by 2050” is an example of a strategy. This pathway is primarily concerned with the energy sector, presently dominated by fossil fuels, and cited for replacement by renewables. Called for here is such a transition, which, however, leaves 30% of the world’s energy supply in the hands of fossil fuels at the level of 120 EJ by 2050. GHC emissions from this level was to be reduced by “carbon-capture-and-storage” (CCS) methods. Strategies derived from this Guide are given below.

4.1 Goals

From the Paris Agreement of 2015 to limit global temperature increases to 1.5 C - 2.0 C by 2050 and from subsequent pathways to net-zero emissions, it is considered that the best means, and likely the only way, of replacing fossil fuels (although some pathways allow for reduced levels of fossil fuels) is through the installation of renewable sources. Solar energy will likely be the largest component of renewable sources. Therefore, the goal will consist of installing PV-EL-FC systems, among other renewables, in view of the following actionable strategies.

4.2 Consider Entities

The IPCC deliberations resulting in the Paris Agreement required that nations submit NDCs.

These public entities, with their various levels as discussed in Section 4.3, must collaborate with

private manufacturing and financial organizations. In addition, colleges and universities must form partnerships with public and private institutions for education, research, and development of renewable energy sources.

4.3 Determine Entity Levels

Although national entities were initially charged with the responsibility of their NDCs, local governments have, to date, achieved greater successes. Today, municipalities, states, and provinces have made substantial progress. A few small countries including Iceland and Costa Rica have become self-sufficient in renewables. Many large countries remain dependent on insecure sources of fossil fuels a discussed in Section 4.7.

4.4 Analyze Sectors

Figure 14.3 in **Part 2** of the guide illustrates the GHG emissions for each of the sectors and its

projected reductions on the path to net-zero by 2050. The utility-scale electric power sector with energy storage is the focus of this guide with complimentary production of hydrogen for the industry, transportation, and building sectors.

4.4.1 Electric Power

The electric sector produces the largest amount of GHG emissions. However, it has also been shown that all sectors must become 90% electrified to reach net-zero GHG emissions by 2050. Addressing both concerns means that electric power must be produced from renewables, primarily solar.

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4.4.2 Industry

The industrial sectors consume about one-third of energy use in most countries. Solar production of electricity will be utilized in water desalination, agriculture, and manufacturing with lower costs and reduced carbon emissions.

4.4.3 Transportation

Fuel cells will power many modes of transportation including cars, trucks, planes, and ships, requiring large amounts of hydrogen fuel. The PEMFC is a leading contender, and efforts are underway to replace the PGM electrodes with earth-abundant components.

4.4.4 Buildings

Although buildings have not been analyzed in this guide, it has been reported that this sector uses 40% of the world’s energy supply in the productions of materials, construction, heating, and cooling. The concept of passive buildings, not considered in this guide, has recently become more important and will result in large reductions in energy demand. However, this decrease, like planting trees, will require a long period of time, perhaps 50-100 years, long after the target date of 2050 for net-zero.

4.5 Evaluate Natural Resources

It is known that renewable energy sources, particularly wind and solar, are variable (VRE). Among the various methods to mitigate these variations for utility-scale grids, the production and storage of green hydrogen has been adopted in this guide. The primary natural resources considered here are (1) solar irradiance, (2) water, and (3) salt caverns for hydrogen storage as discussed in **Part 2**.

4.6 Address Critical Materials Limitations

Among the natural resources as discussed in **Part 5**, the global installation of PV, EL, and FC systems will encounter limitations of certain chemical elements utilized in solar panels as well as in electrlyzer and fuel cell electrodes and electrolyzers. For example, substitutes for silver contacts in solar panels and the platinum group of metals for electrolyzers and fuel cells must be developed with comparable performances. Research results given in **Part 3** illustrate some of these paths.

4.7 Project Energy Supply and Demand

The world’s annual use energy has been projected in **Part 1** of this guide to be a constant level of 500 EJ per year. To meet this need, the system energy for this global supply is also assumed to be this level during the period of 2020 to 2050. Demand management techniques, including increased user efficiencies, should be emphasized.

Due to system inefficiencies, the necessary energy supply inputs will be several times the demand output energies of the models considered in this guide. For the PV-EL-FC models discussed in this guide, the system efficiency is approximately 20%. In these cases, the necessary PV input energy will be five times the FC output energy connected to the grid. For example, if a grid requires 10 EJ per year from the FC, the PV array must supply 50 EJ per year.

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4.8 Weigh Energy Import-Export and Security Factors

Countries will import, export, or be in a self-sufficient position (possible combinations of each) as these needs relate to their energy supply and demand requirements. Section 13 of **Part 2** gives examples. These considerations will directly affect the country’s energy security.

4.9 Scale PV-EL-FC Systems

Countries, regions, or grid developers can estimate the size of their systems by linearly scaling their energy needs relative to energy models of this guide. For example, a country which uses 10 EJ per year would require a system of 10/500 or 2% of the WSC World Model C as given in Part 2, Table 14.7. These estimates will include the sizes of solar photovoltaic panels, electrolyzers, and fuel cells, as well as the necessary quantities of water and hydrogen storage. Digital models could also be constructed for dynamic analyses.

4.10 Address Barriers and their Solutions

4.10.1 Technical Barriers

The conversion efficiencies of solar PV devices have increased in laboratory settings from 20% to 40%. Photon efficiencies often exceed 80%. Manufacturing procedures have resulted in durability and lifetime extensions. Limited materials such as silver must be replaced with other conductors.

Electrolyzer systems have now exceeded 1 GW. Fuel cells remain smaller in output power but are increasing. Efficiencies and durability of components, stacks, and systems require improvements. Critical materials limitations of PGM and rare earths must be addressed with substitute materials.

4.10.2 Costs

The cost of PV arrays has decreased by factors of 5-10 in recent years, reducing the largest cost component of green hydrogen. The current cost of hydrogen is $2.00 to $3.00 per kg making this gas still uncompetitive. Projections of cost reductions show that hydrogen will be available at $1.00 by 2050.

4.10.3 Evaluate Required Rates of Growth

Annual growth rates of solar photovoltaic (PV) installations appear to be feasible for global supplies. However, the necessary growth rates for electrolyzers (EL) and fuel cells (FC) to meet global needs for hydrogen production and grid power may be problematic.

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Annual growth rates of solar photovoltaic (PV) installations appear to be feasible for global supplies. However, the necessary growth rates for electrolyzers (EL) and fuel cells (FC) to meet global needs for hydrogen production and grid power may be problematic. These rates, r, can be determined from the relation, F = P(1 + r)n, where F, P, and n are the future value, present value, and number of periods, usually years.

Annual growth rates of solar photovoltaic (PV) installations appear to be feasible for global supplies. However, the necessary growth rates for electrolyzers (EL) and fuel cells (FC) to meet global needs for hydrogen production and grid power may be problematic.

4.11 Continue Research and Development

Although great strides have been made during recent years in photovoltaics, electrolyzers, and fuel cells, improvements in both fundamental understandings (catalysis, for example) and in technical implementations can still be achieved. Some of these areas are outlined in **Parts 1, 2, and 3** of this Guide. **Part 4** demonstrated that the other methods of hydrogen production will likely remain in the research stage and continue to be uneconomical until after the target date for net-zero emission in 2050. **Part 5** emphasized that new components with expanded capacities will require not only earth-abundant materials but understandings of the photonic and electrochemical processes within their components.

Examples of primary strategies for the goal of limiting global warming are “Net Zero Emissions by 2050” and “100% Renewable Energy” as outlined in Table 2. These two goals differ because “Net Zero” can be achieved with a significant level of fossil fuels, typically 30%, whereas “100% Renewables” relies totally on sources such as solar and wind. The term, “Net Zero Emissions” may refer to either CO2 or to all green-house gases (GHG) which would include methane, CH4, the primary component of natural gas which also produces CO2 when oxidized (burned). Methane, itself, causes 30 times as much atmospheric warming as CO2 because, with four atoms, it has more quantized vibrational modes which absorb the infrared radiation emitted by the earth’s surface at a temperature of approximately 20 C.

Figures 2 and 3 illustrate these processes [2]. With the solar surface temperature of approximately 5,700 C, its Planck radiation (**see Part 1 Appendix**) lies in the visible portion of the spectrum. This radiation is reflected or absorbed by earth’s atmosphere, and a portion of the sun’s radiation is transmitted to the earth’s surface. The earth then absorbs this radiation and emits it back into space as long-wavelength radiation in the infrared region or heat. Some of these wavelengths coincide with the frequency of the GHG molecular vibrations (E = hν/λ) and are absorbed causing the molecules to move faster which heats the atmosphere.

It should be noted that without CO2 in the atmosphere, planet Earth would be nearly as cold as Mars. Over periods of time longer than recorded history, the concentration of CO2 has been about 0.03% (300 ppm). Beginning in the Industrial Revolution ca. 1750, this concentration began to increase to its current level of more than 0.04% (400 ppm). It is this **excess CO2** which has caused the atmospheric warming. In addition, this warming trend is strongly correlated with the CO2 concentration increase over time as shown in **Part1** of this guide.

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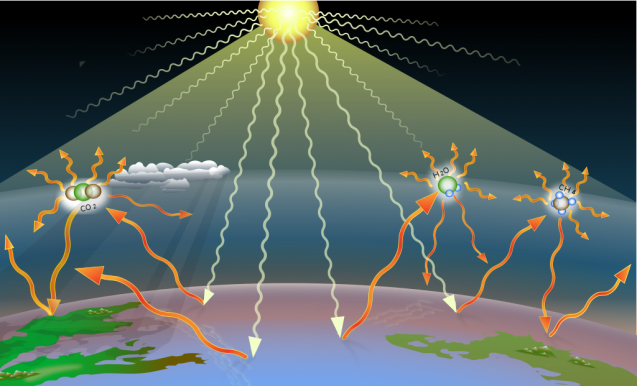


Figure 2. Diagram showing the transformation of sunlight into infrared radiation [2].

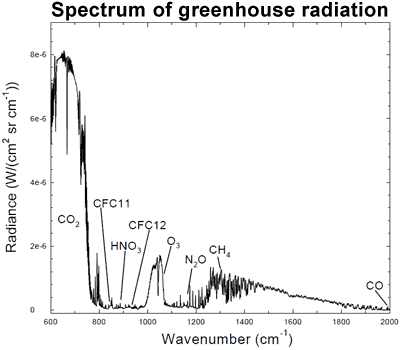


Figure 3. Spectrum of Earth infrared radiation and GHG absorption lines [2].

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A comparison of the two strategies to limit global warming is shown in Table 2, where is can be seen that some overlap of the components occurs.

Table 2. Comparison of two energy strategies.

|  |  |
| --- | --- |
| **“Net Zero Emissions by 2050”** | **“100% Renewable Energy”** |
| International Energy Agency-2023 update [3]  A portion of the Pathways are given here:  The case for energy transformation  August 2023 hottest month on record  37 Gt CO2 emissions in 2022 new record  Temperature increases > 1.5 C may be irreversible  International  Increase commitment to the IPCC Nationally  Determined Contributions **(NDCs)**  Achieve deep emissions reductions by 2030  Triple renewables capacity  Accelerate electrification  Reduce methane emission  Accelerate long lead-time options  CCUS, hydrogen, bioenergy, infrastructure  Energy security  Bridge gap between critical mineral supply/demand  Scale up clean energy technologies  Scale down fossil fuels  Equity  Accelerate deployment in emerging-market and  developing economies  Enhance clean-energy affordability  Manage the employment transition | National Renewable Energy Laboratory [5]  The US NREL proposed six potential strategies to achieve 100% RE electricity:   1. Variable RE, Transportation, **Diurnal Storage** 2. Other RE sources, e.g. hydro and biomass 3. Nuclear/Fossil with Carbon capture 4. **Seasonal Storage** 5. CO2 Removal 6. Demand Side Resources   The difficulty/cost of increased RE deployment associated with increasing the fraction of annual energy from RE is shown graphically in Figure 4.  These challenges would be relevant to the models  given in the World Solar Guide, **Parts 1 & 2.** |
| Climate Action Tracker (CAT) [1]  Unfortunately, many countries wo participated in the Paris Agreement have failed to live up to their **NDCs**.  The year, 2080, is seen as the date for Net Zero at  1.5 C.  These deficiencies are tabulated in this reference. | Research Paper [6]  Optimal sourcing strategy may assist achievement of <<<**NDCs** when the government subsidy scheme does not cover renewable energy target due to legal limits.  Involves 300 + global companies.  Cost minimization strategy:  Min Ʃn C1 + C2 + C3 -R  (1 + r)n |
| Plan A [4]  Oriented toward business operations and citing the lack of compliance to IPCC **NDCs** by several countries,  Plan A advocates the following Oxford Principles:   1. Cut emissions first 2. Shift to carbon removal compensation 3. Shift to long-lived carbon storage 4. Support the development of Net Zero aligned   carbon compensation. | One Earth [7]  A joint declaration of the global strategy group calls for 100% renewable energy in the electric power sector by 2030 and 2035 in other sectors.  This view can be contrasted with organizations which have demanded an achievement of only 70% renewables by 2050. |

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The difficulty/cost of integrating renewable sources into electric grids [8] is shown in Figure 4.

This problem was considered earlier in **Part 7** with the “Duck Curve” model.

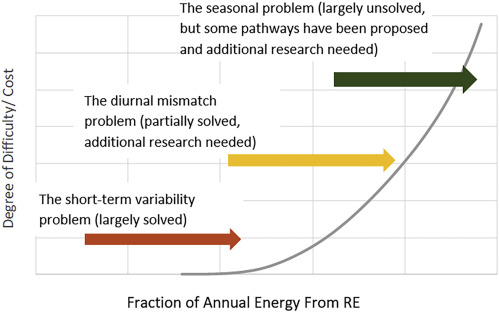


Figure 4. Challenges in reaching 100% renewable electric. Image from Ref. [8]

The models in **Part 2** of the World Solar Guide considered PV-EL-FC systems which can be scaled to KW-MW-GW sizes for national and regional energy consumption levels. These models are not engineering designs but were presented for two purposes.

First, the sizes of the PV arrays were discussed. The area of the hypothetical world model is about 3.5 x105 km2 for “day-time” power production. However, when the assumed capacity factor, CF, of 25% and the calculated system efficiency, η, is considered, this required area becomes 1.8x106 km2. The necessary PV power, Pout is determined by the relation,

Pout = Pin = 15.9 TW = 303 TW

(CF)η (0.25)(0.21)

where Pin is the theoretical power required for a world annual energy consumption of 500 EJ.

From the power requirement, areas of the PV-EL-FC components can be determined.

The second aspect is the amount of component materials (electrodes, electrolytes, etc.) required for these large areas. **Part 4** of the Guide evaluates these material requirements and power limitations in terms of **critical** materials such as the platinum group of metals, PGM, and **earth**-**abundant** materials.

The system models and components considered in the World Solar Guide are examples of a research-and-development efforts which will be necessary in renewable-energy transition strategies.

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5. Economic Growth, Environmental Sustainability, and Renewable Energy

5.1 Economic Growth

An abbreviated outline of economic thought is given in Table 4 Ref. [9]

Table 4.

* Ancient economic thought (before 500 AD)
* Economic thought in the middle-ages (500-1500 AD)
* Mercantilism and international trade (16th-18th centuries)
* Preclassical (17th-18th centuries)
* Classical (18th-19th centuries)
* Neo-classical (19th-early 20th centuries)
* Alternative schools (19th century)
* World wars, revolutions, depression (earth-to-mid 20th century)
* Keynesianism (20th century)
* Chicago School of Economics (20th century)
* Post World War II and globalism (mid-to-late 20th century)
* Post 2008 financial crisis

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5.2. Economic Growth and Environmental Sustainability

The relationships between economics and the environment were first discussed in the early-to

mid-20th century [10] in which it was generally concluded that economic growth produced

negative impacts on the environment. During this period, concepts of renewable energy were

little known.

**Sustainable development** is stated as “an organizing principle that aims to meet human development goals while also enabling natural systems to provide necessary natural resources and ecosystem services to humans.” Six central capacities to achieve sustainable development are shown in Figure 5.

In a related concept, **sustainability** is “a social goal for people to co-exist on Earth over a long period of time.” The three dimensions of sustainability are shown if Figure 6. References for these concepts and figures are given [9].

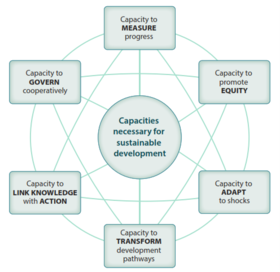
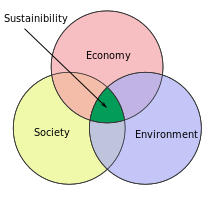
 

Figure 5. Six capacities for sustainable Figure 6. Sustainability dimensions [10].

Development [10].

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5.3. Economic Growth, Economic Sustainability, and Renewable Energy

A recent study [11] considered the relationships between economic growth, the environment, and renewable energy among the G7 countries as shown schematically in Figure 7. Models utilizing simultaneous equations determined these relationships.

GDP

EFP REC

Figure 7. Interrelationships of EFP, GCP, and REC Ref. [11].

In this diagram, GDP represents, gross domestic product, EFP is the ecological footprint, and REC is renewable energy consumption. The study found relationships between these variables which are depicted in Figure 8.

GDP EFP EFP

REC GDP REC

Figure 8. Schematic diagrams of GDP, EFP, and REC relationships Ref [11].

Thus, renewable energy consumption exhibited the dual effects of increasing gross domestic product and decreasing the ecological footprint. As found in previous investigations, gross domestic product, alone, increased the ecological footprint.

A similar study considered these interactions in Columbia using modified ordinary least squares, dynamic least squares, and autoregressive distributed lag estimators [12]. The study found growth-induced emissions on an unsustainable path. It was also seen that renewable energy contributed to environmental quality. A compilation of these types of papers in which policy implications are stated is given by sciencegate.com [13].

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6. Energy Transition in the United States (a Spoof)

Consider the following fictional transition from fossil fuels to renewables in the US. The federal government recently closed a gas pipeline from Canada to the US. This pipeline company, Methane, Inc., was a wholly-owned subsidiary of a large international oil giant. Hank Snodgrass, age 52 is an employee of Methane, who has been with the company for 27 years. An hourly employee, he earns $35 per hour or about $70,000 a year. He is looking forward to a comfortable retirement and has accumulated a small fund in his 401(k) plan. His daughter, Katie, is a student at South Dakota State University where she is also a cheerleader. SDSU has an excellent football team, but cheerleaders are not given scholarships. In addition to college expenses for their daughter, Hank and his wife, Harriot, still owe payments on a home mortgage.

Upon learning of his termination from Methane, Inc., wife, Harriot, is extremely distressed as similar employment in the area is unlikely. Hank could probably find work at the local Walmart store as a Greeter, but the wages world be only $15 per hour. A newspaper story told of a new solar plant in Texas which might be a good opportunity for Hank with minimum culture shock.

This new plant, TexSun, is planning to install a “solar farm” (or “solar ranch” in Texan terms) of photovoltaic panels near Amarillo, a location with high solar irradiance. Texas does not have federal lands, but a local rancher will sell the company 10 sections (10 square miles or 6,400 acres). The company has hired several new employees and requires additional persons.

One candidate is William Robert (“Billy Bob”) Jones (no relation to Jimmy Jones, owner of the Dallas Cowboys), age 24, and a former All-State Linebacker (LB) for the Amarillo Armadillos high-school football team. His sidekick, Nimrod Bipp, was not a jock but is considered a good old boy, although somewhat of a nerd. Both men were offered permanent positions with TexSun. Hank applied for a position but was unsuccessful, most likely due to his age. This net employment is seen in Table 5. There may be renewables gain, but there would also be pain.

Table 5.

Employment score: Fossil fuels -1

Renewables +2

Net employment + 1

Hank accepted a job as a Walmart Greeter, and Harriot took a position at a local “Dollar” store. Katie hired on flipping burgers part-time while maintaining her studies. All was not lost as the Snodgrass family was able to pay college tuition and their home mortgage.

The above mythical scenario (or “Spoof” in American slang) might be an exaggeration, although companies and governments have been known for their drastic measures rather than for careful transition plans. A simple solution here would have been the policy of energy employers to offer their employees other positions. Such a fossil-to-renewable coordination would lead to better overall results. Countries with no fossil fuels might not face this dilemma; they will, however, be required to provide different types of transitions. Highly populated areas in Europe, for example, may have to choose between land-use for solar installations or agricultural use.

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7. Energy Transitions Plan (for Real)

7.1. Employment Transition Plans

This Guide has been written as a resource for developers of renewable energy, and employment measures are an important part of this transition. The plans referenced here are essentially for technician-level employees who may transfer from energy, industrial, or transportation sectors into renewables. They may also enter this market as newly trained professionals. A few transition plans are summarized in Table 6.

Table 6. Comparison of transition plans.

|  |  |  |  |
| --- | --- | --- | --- |
| **Reuters [14]** | **Research Paper [15]** | **IEA [16]** | **IRENA [17]** |
| Clean energy technology will create 14 M new jobs by 2030. Another 16 M in building and transportation.  5M employees in fossil fuels will not readily transfer to clean energy.  Training new employees is an urgent challenge for policy-makers, businesses, and educators.  Keeping people in their communities is often a missed focus. | Techno-economic models assume labor is available  “just-in-time,” but barriers to labor supply occur.    These barriers include:  1. Smaller size of labor  markets and key jobs.  2. Boom-bust cycles.  3. Competition for labor.  4. Disadvantages areas in under-employed populations.  5. Demographic changes such as aging  Policies should develop local employment for a “fair and fast” transition.  Policy options include:  1. Development profile to scale regional work force.  2. Investment in training and management as part of the eco-system. | Energy employment is shifting from fossil fuels to clean energy.  The world energy sector employs 65 M, half in renewables.  The energy sector requires higher-skilled workers than other industries.  A large employment growth potential is seen  for renewables with 14 M and 16 M in related areas.  Key to energy transition:  make employment growth “people centered.” | 1. Decentralized renewables:  Decentralized solutions provide power and employment in remote areas.  2. Millions of new jobs:  Employment will expand substantially.  3. Industrial policy:  Vulnerability to global supply-chain disruptions is driving policy measures to strengthen local capacities.  4. Workforce development and diversity:  Education and training must be expanded.  5. A just transition:  Labor rights and social dialogue are indispensable.  6. Systematic change:  Achieving this transition  consistent with climate stability requires faster renewable deployment. |

From Table 6, it is apparent that the views of IEA and IRENA are general and “macro.” The Reuters article cited specific local experiences in the Bahamas, Virgin Islands, and South Africa. The academic model provided a quantitative analysis of employment scenarios. In all examples, **employment** is a key-stone of the **energy transition** process.

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7.2. Examples of Transition Plans

Discussed here is a simplified, general transition plan for the replacement of fossil-fuels usage with renewable sources. Certainly, every country, region, or municipality will have different needs, but there may likely be some common threads. These renewable sources are limited to those described in previous portions of this guide, that is, PV-EL-FC systems which produce electrical power for grids and hydrogen for other sectors as seen in **Part 2**. Shown in Figure 9 is a schematic diagram of a conceptual transition plan for three parties, management, suppliers, and consumers. Such constructs are common among business models. It can be noted that this plan is derived from analyses of **Parts 1, 2,** and **6**.

Management

National

Regional

Municipal

Government/Business Partners

Sector Analyses

Tactical Plans/Strategic Plans

(Short-Term)/(Long-Term)

Consumer Demand

Annual energy demand

Material requirements to meet energy

demand

National energy and materials security

Demand temporal redistribution and

Reduction

Advocate increased efficiencies

Supply/Production

Natural resources

Solar irradiance

Water for EL hydrogen production

Salt deposits for hydrogen storage

and FC use

Land use for solar PV panels

Critical Materials

Earth-abundant materials

Investment

Materials supply chain stability

Replace scare materials with

earth-abundant elements

R&D spectrum

Environmental/sustainability standards

Increased reclamation and recycling

Balance Supply and Demand

>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Figure 9. Conceptual management scheme for an energy transition plan.

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As a second example of a transition plan, consider the fictional country, “Solterra.” This country has a population of 40 million, an area of 300,00 km2, located in a region with a solar irradiance of 2,190 days per year of sunshine (6.0 hours per day). One border is adjacent to an ocean which offers the option of direct electrolysis or desalination in the production of hydrogen. A solar PV installation will produce direct power to the grid as well as hydrogen production for other sectors. A salt deposit will provide an estimated 1.8x109 Nm3 of hydrogen storage for fuel-cell power during the “night-time” hours (18.0 hours per day). The country’s annual energy demand is 2.78x1012 KWh, and the country has stated that it intends to develop 50% of its energy requirement. 1.39x1012 KWh from solar-hydrogen sources with the balance supplied by other renewables and fossil sources.

The federal government has formed alliances with several fossil-based utility and industrial firms who will commit investments to this project, supplemented by government grants. Several technicians of these firms are interested in seeking employment in this renewable system. Two universities offer course-work leading to four-year degrees in renewable energy and graduate-level research programs for the utilization of earth-based materials in PV-EL-FC systems. A few utility and industrial firms have expressed interests in developing these materials and systems to the commercial level.

Utilizing the calculation methods of **Part 2**, PV-EL-FC results can be determined, with Figure 9.1, and Table 14.7 as references.

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8. A Pedagogical Note

8.1 General Comments

**World Solar Guide** has been written primarily as a resource for developers of renewable energy. “Pedagogical” sections (some would say “Pedantic” sections) have been included for instructors and students in the Appendices. Advocates of renewables and energy associations may also consider this site informative.

As a former engineer, research scientist, and program manager in fuel-cell development, this writer is familiar with most technical aspects of the guide. Its preparation has also been a learning adventure, and new areas of interest arose. Having experience in “materials science,” particularly “conductors,” “semiconductors,” and “insulators,” the research aspect of writing this guide was rewarding. These materials find their places in solar cells, electrolyzers, and fuel cells which are the major systems discussed in this guide. While not considered in detail here, electric grids and renewable-energy infrastructure will also become increasingly important.

The most urgent need for the world-wide transition to renewable energy will be the development of improved materials which are also **earth-abundant**. For example, new semiconductors and metallic electrical conductors will be required for solar cells. In addition, electrode and electrolyte components for electrolyzers and fuel cells will need, for example, perovskites, transition metals, and carbon-based materials. However, even though many materials are critically limited on a global scale, the R&D efforts in understanding fundamental processes and developing workable components and systems are equally important.

Students will find it necessary to select a particular discipline of concentration in which to become productive and “expert” over career lengths. The choice might be between conventional water electrolysis and other methods of hydrogen production. Although the method of electrolysis has been known for two centuries, some aspects of fundamental processes such as catalysis remain unclear.

Although this guide has focused on the “science,” particularly the physics and (electro)-chemistry, aspects of renewable energy, practical devices and systems will require education and careers for large engineering developments such as smart electric grids.

A new way of thinking will be required. Instead of extracting chemical energy from the earth, electromagnetic energy will be captured from the sun. New calculations will emerge. In addition to Avogadro’s number, 6.02x 1026 mol-1 inMKS units, for example, the annual world energy demand, 500 EJ, can be compared with the energy of a single visible solar photon, 3.8x10-19 Joule. This ratio is 1.3x 1039 with these photons arriving on earth at the rate of 2x1021 photons-m-2-sec-1 as discussed in **Part 1** and the associated appendices. Energy-related careers in business, government, and the law will arise. For these disciplines, science-technology knowledge at the Bachelors (four-year) level would be advantageous and perhaps mandatory.

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8.2 Personal Experience

As a graduate student, this writer began an investigation of the III-V semiconductor, gallium-arsenide, GaAs. It was known that this semiconductor exhibited a higher electron mobility than silicon and, thus, may have resulted in faster computer operations.

The precursor studied was known as an MOS (metal-oxide-semiconductor) device in which the oxide layer was produced by anodization of GaAs samples in a liquid electrolyte at a constant- current density. The samples were then measured by the capacitance-voltage (CV) method. Due to “dangling bonds” at the oxide-semiconductor interface, the CV data showed that the device did not charge and discharge properly meaning that it could not be used as a computer “chip.”

Although this phase of the research did not produce a working computer precursor, the anodization process was further investigated by Rutherford Backscattering Spectrometry (RBS). In this technique, helium ions are accelerated to energies of about 1 Mev, and the spectra show a cross-section of the oxide with typical thicknesses of about 100 – 300 nm. Xenon markers were implanted by the Chalk River Nuclear Facility in Ontario, Canada and then measured to determine a transport number of 0.17 meaning that the oxide was formed by the outward migration of semiconductor atoms (17%) and by the inward migration of oxygen atoms (83%).

GaAs is currently not used as computer components, but it has been evaluated in solar PV cells. This compound is also a critical/scarce and expensive material, making it unsuitable for large-scale solar-panel installations.

One lesson learned in this investigation is that research follows is own paths, often in surprising directions. These paths may not lead to useful devices, but the knowledge gained in their studies can be translated to other areas.

8.3 Suggested Areas of Study and Research

Currently, the PV-EL system is seen to be the most viable means of producing large quantities of hydrogen. The PV-EL-FC system can then be used to power electric grids.

8.3.1. Solar Photovoltaics (PV)

Solar PV technologies are mature, with many silicon panels now installed in “solar farms” around the world. The abundance of silicon and the dramatic reduction in cost will ensure that these cells continue their journeys towards “net-zero” by producing electricity and by powering electrolyzers for hydrogen. Efficiencies may be increased with other materials and technologies such as perovskites, thin films, and multi-junction devices. Emphasis should be placed on the utilization of earth-abundant materials as a total world area for these panels of approximately

1.5 x 106 km2 will be required.

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8.3.2. Electrolyzers (EL)

The alkaline, typically KOH, water electrolyzer with nickel electrodes is currently the most productive device for large-scale hydrogen production. The anion exchange membrane, AEMEL, is under R&D work in many labs.

8.3.3. Fuel Cells (FC)

Large-scale, commercial fuel cells are presently not available. This guide is primarily concerned with the development PV-EL-FC systems for grid power, but fuel cells will also be used for vehicles in the transportation sector. Candidates include the PEMFC and AEMFC. Fuel cells will also power railroads, planes, and ships.

8.4 Research and Development Spectrum

The paths of research and development can be expressed as a “spectrum” of activities performed by different entities as shown schematically in Figure 10.

|  |  |  |  |
| --- | --- | --- | --- |
| Basic Research  Universities | Applied Research  Government Labs | Development  Industrial Labs | Production  Industrial Manufacturers |

Figure10. The R&D spectrum.

Basic research is usually performed at the university level with a focus on the fundamental understanding of processes including, for example, in the area electrolysis, electrode reactions, catalysis, and component morphologies (see **Part 3**). Although the catalysts, platinum, iridium, ruthenium, and rhodium will continue under investigation, researchers are actively pursuing earth-abundant elements as PGM replacements in electrolyzer and fuel-cell applications.

Government labs support applied research. In the area of renewable energy, systems such as PVs, ELs, or FCs may show promising levels of catalytic activities, improved efficiencies, or longer periods of durability. They may also fund research at small companies with mandates to develop commercial products (see **Part 2**). Replacements for silver contacts in PV cells such as copper and aluminum would be included in these projects.

The need to install large-scale renewable energy systems with limited resources and environmental restrictions requires industrial manufacturers to also reclaim materials at end-of-life intervals even if they are earth-abundant. These requirements become more severe when the system components contain, for example, the platinum group of metals (small scale, near term) or limited quantities of transition metals including cobalt, chromium, and tungsten as discussed in P**art 5**.

Entity partnerships are essential across the spectrum as they combine various areas of expertise and shared funding with the objective of developing products for identified markets. These concepts are discussed further with marketing and management features in **Part 1.**

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8.5. Career Choices

The study/career choice of alternative methods such as photocatalysis may result in radical new methods of hydrogen production. On the other hand, these methods may continue to follow their photosynthetic analogs with extremely low efficiencies. PV-EL currently appears to be the most viable means of producing hydrogen on a global scale. Both fundamental research and large-scale developments with earth-abundant materials will be necessary. These choices are not simple and will involve considerations of areas other than academics such as the location in one’s own country or in other countries. Encountering new countries and cultures can be rewarding; these experiences may also have negative consequences. Preparation is essential for factors concerning immigration/citizenship status, family matters, housing, taxes, and retirement.

Not discussed in the guide are components of the bio-sphere. Two-thirds of the earth’s surface is covered by water with an atmospheric envelope. Oceanography and meteorology, with the atmosphere experiencing higher temperatures, will become increasingly important. Other areas such as agriculture, forestry, and bio-energy will face new challenges and opportunities. Basic academic disciplines include biology, zoology, and organic chemistry to name a few. It is this sphere which sustains life, and renewable energy is only a means to this end.

The PV-EL-FC systems presented in the guide are **active** systems. As buildings require large amounts of energy, **passive** designs using solar-architecture techniques will lessen the demand for other forms of energy. The solar irradiance of 1,000 watts per square meter which produces electricity in PV panels is also available to heat buildings.

PV-EL-FC systems will likely provide most of the world’s renewable energy through the transition period tentatively ending in 2050. Other forms of hydrogen production, which utilize direct interactions of solar photons and water species, were also considered in this guide, with the most promising method being photoelectrochemical (PEC). Laboratory results, numerically scaled to commercial levels, currently exhibit production rates exceeding those of the indirect PV-EL systems.

An outline of a proposed education curriculum for these forms of renewable energy is presented below in Section 8.6.

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8.6 Proposed Educational Curriculum Outline

Universities typically offer courses in Colleges and Departments such as Chemistry, Physics, Mathematics, Engineering, and Computing. Business and Law Colleges may also find themselves involved in renewable energy sources.

While it will not be feasible for faculty and students to pursue all the courses outlined below, they suggest a progression from general to specific areas, not only at the educational level, but also for professional pursuits in research and development. An outline of such a progression is given in Table 7 for majors in chemistry and physics. Research in areas of PV-EL-FC systems can begin at the graduate levels. Basic knowledge of electrochemical and physical principles is still pursued with **critical** elements. Large-scale installations require development of components with **earth-abundant** materials.

Table 7.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Level** | **Physics**  **Physics**  **Major** | **Research**  **Photovoltaic – PV**  **WSG Parts 1,2,4** | **Research**  **Photoelectrochemical –PEC**  **WSG Parts 1,2,3,4,5** | **Research**  **Electrochemical – EL**  **FC**  **WSG Parts, 1,2,3,4** | **Chemistry**  **Chemistry**  **Major** |
| Ph.D.  Original  research  Related courses  **Earth-abundant**  **materials**  Alkaline, acid  electrolytes | Required  coursework | Semiconductors  Chalcogenides Perovskites  Silicon  Multi-junction  NREL materials | Photoanode Photocathode  OER HER  HOR ORR | Anode Cathode  OER HER  HOR ORR  Nano structures  Transition metals  Carbon materials | Required  coursework |
| M.Sc.  Independent  research  Related courses  **Critical**  **materials**  Alkaline, acid  Electrolytes | Required  coursework | Semiconductors  Silicon  perovskites | Photoanode Photocathode  OER HER  HOR ORR | Anode Cathode  OER HER  HOR ORR  Pt IrO2 | Required  coursework |
| Year 4 | Semiconductor  Physics  Solid State  Physics |  |  |  | Density  Functional  Theory  Electrochemistry  Reactions  Catalysis |
| Year 3 | Quantum  Mechanics  Math |  |  |  | Quantum  Mechanics  Math |
| Year 2 | Electricity and  Magnetism  Electric circuits  Mechanics  Optics  Math |  |  |  | Physical  Chemistry  Organic  Chemistry  Math |
| Year1 | General  Physics  Chemistry  Math |  |  |  | General  Chemistry  Physics  Math |

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Whatever the choice, students are encouraged to pursue studies and careers in renewable energy and related subjects. It would also be beneficial to establish networks with colleagues. These experiences will not only be rewarding, but the efforts will contribute towards making our planet sustainable over time periods not measured in the lifetimes of its resources.

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GOOD LUCK, BON CHANCE, KOUN O, HELD OGLYKKE, BUONA FORTUNA,

MAZEL TOV, HAZANA TAYIBAN WAFAQAK ALLH, SEMOGA BERUNTUNG,

BUENA SUERTE, ZHU NI HAO YUN, LYCKA TILL, KALI TYCHI, VIEL GLUCK,

UA PAKO KAAMAYAABEE MILE, BAHATI NIEMA, HAENG-UN-EUL-BIBNIDA

Jon D. Canaday

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9. Conclusions

Major scientific and technical improvements for PV, EL, and FC systems have occurred during the past 10-20 years. These improvements have also resulted in significant cost reductions in the photovoltaic power as well as in the production and utilization of hydrogen. R&D efforts must continue for fundamental understandings of, for example, catalytic activity, and for improvements in efficiency, durability, production techniques, and recycling measures. The earth’s “renewable-energy shortage” is essentially a “materials shortage.” Development of new and improved component materials which are also **earth-abundant** is critically important. These new materials may exhibit inferior characteristics relative to those shown by the **critical** elements as measured by electrical conductivity for PV devices as well as catalytic activity, efficiency, and durability for EL and FC systems. However, the lower costs of these abundant materials will accelerate the reduction in hydrogen costs towards the projection of $1.00 per kilogram.

Implementing a satisfactory transition from fossil fuels to renewable energy sources will pose serious challenges for many countries, regions, and municipalities in the coming generations. These transitions will require policy and strategy statements with detailed plans among entity levels and sectors. National transition measures should also result in improved energy security while at the same time maintaining collaborative efforts between nations. The development of world-wide transitions plans will likely be more difficult than the technological and financial aspects of a “second industrial revolution.”

A diversity of views concerning required dates for achieving the goals of “Net Zero Emissions by 2050” and “100% Renewable Energy” currently exists. Carbon Action Tracker predicts a Net Zero by 2085 due to non-compliance by several countries, and the global strategy group of One Earth urges 100% RE by 2030-2035.

Readers and developers of renewable-energy systems are encouraged to evaluate various natural renewable sources, limitations, models, and pathways to adopt policies and strategies which are most suitable in adapting these resources to their needs.

It is hoped that the review of **World Solar Guide** has been a learning experience in providing useful tools for designing and producing energy systems which are economically viable, environmentally sustainable, and energetically renewable.

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