1

 **World Solar Guide**

 **Part 10**

 **n = 9**

 **Summaries = Ʃ Parts i**

 **i = 1**

 **Jon D. Canaday, Ph.D.**

 jon.canaday@world-solar-guide.com

 **ƩƩƩƩƩƩƩƩƩƩƩ**

 **Ʃ**

 **Ʃ**

 **Ʃ**

 **Ʃ**

 **Ʃ**

 **Ʃ**

 **Ʃ**

 **Ʃ**

 **ƩƩƩƩƩƩƩƩƩƩƩ**

 **ƩƩƩƩƩƩƩƩƩƩ**

 **Ʃ**

 **Ʃ**

 **Ʃ**

 **Ʃ**

 **Ʃ**

 **Ʃ**

 **Ʃ**

 **ƩƩƩƩƩƩƩƩƩƩ**

 Copyright 2023 © Jon D. Canaday

2

 **World Solar Guide**

 **Part 10**

 **Summaries**

General Summary

The **World Solar Guide** analyses in **Parts 1 - 9** have been prepared as a resource for developing global renewable-energy assets. These units, 500 pages (24 MB) in total, are presented in the formats of (1) general reading, (2) textbook materials with tutorial sections, and (3) research papers with literature references. A few of the primary points are given here:

* The Paris Accord Agreement for limiting global warming and eliminating CO2 emissions by 2050 was signed by 190 countries in 2015.
* Literature **“Pathways”** to achieve this goal of net-zero CO2 by 2050 through the replacement of fossil fuels with renewables during this **transition** period were reviewed.
* The annual global energy demand in this guide is assumed to be 500 EJ, with 450 EJ electrical and 50 EJ hydrogen, corresponding to a solar power of 15.9 TW for a capacity factor and system efficiency each of 100%.
* As solar photovoltaic (PV) energy is variable, storage systems are necessary. A capacity factor of 25 % corresponding to six hours of daily sunshine is assumed.
* Electrolyzers (EL) produce hydrogen and fuel cells (FC) utilize the stored hydrogen to produce electricity which is fed to electric grids (EG).
* The total efficiency of this PV-EL-FC system was determined to be η = 20%.
* Due to the capacity factor of CF = 25% and system efficiency of 20%, the input power will be about 300 TW: Pin = Pout/CF(η). This power level may be an overestimate due to the exclusion of other renewable sources, but it will most likely be in the range of 100-150 TW. These estimates exceed “net-zero CO2 emissions pathway by 2050” levels by factors of 10-100. The “100% renewables scenarios” are also considered.
* Scalable **“macro-models”** with hydrogen storage were developed in **Part 2** to simulate the energy supply and demand quantities at national, regional, and world levels.
* The components of the subsystems include PV cells and EL and FC electrodes.
* **“Micro-models”** were utilized in **Part 4** to estimate component (solar-cell and electrode) material and electric-power limitations together with earth-abundant materials research.
* Six natural resources for renewable solar energy were identified: (1) solar irradiance, (2) water for electrolysis, (3) salt caverns and deposits for hydrogen storage, (4) land for PV,
* (5) critical/scarce chemical elements, and (6) earth-abundant materials.
* R&D in abundant materials (transition/carbon-based) may be called **“nano-models.”**
* The solar irradiance at the earth is about 10,000 times the earth’s needs. **Critical** elements necessary to produce power will be limited and/or inadequate.
* This **transition** will require that **earth-abundant** materials be developed rapidly as replacements for the limited elements in the PV-EL-FC-EG sub-system components.
* The production of these elements will require expanded mining and reclamation.
* Management and balance of energy supply/demand can be achieved with smart grids.
* Policies and strategies for the implementation of these energy sources were developed.

 3

Part 1 – The Case for Solar Photovoltaic Energy

The Paris Agreement determined that the primary means of mitigating atmospheric CO2 emissions and global warming will be the replacement of fossil fuels with renewable energy sources. Among these sources, solar energy, and solar photovoltaic (PV) in particular, are considered the most prominent contributors. **Part 1** estimates the world panel area for the “day-time” solar production to be about 3.5x105 km2. PV estimates for regions and countries are also given. The appendix provides pedagogical descriptions of early physics leading to electromagnetic radiation, the quantum nature of this radiation, and solar PV devices.

Part 2 – Storage Requirements of Variable Solar Energy

Because solar energy varies with time and location over the earth’s surface, its storage for use in non-solar periods is crucial. This storage, on a global scale, will primarily be in the form of hydrogen. Scalable photovoltaic-electrolysis-fuel cell (PV-EL-FC) systems which will produce hydrogen and electricity are described. The storage system for the eighteen-hour “night-time” use will be larger than the six-hour “day-time” system. This difference will a factor of about five due to the assumed capacity factor of 25% and efficiency limitations of the EL and FC systems.

The global annual energy demand is taken to be 500 EJ during the period of 2020-2050. This level may be an underestimate if demand increases. On the other hand, detailed energy requirements for the various sectors, including passive buildings, have not been considered, lowering this demand. This energy demand is consistent with other estimates in **Part 1**.

A hypothetical World Solar Guide **“macro-model”** specifies 450 EJ per year for electric grid input and 50 EJ annually for hydrogen production allocated to other sectors. The total world PV panel area for these levels is approximately 1.8x106 km2. MW-GW electrolyzers and fuel cells will be required. The alkaline electrolyzer is considered the most viable type presently. The power requirement will be within the range of 100-300 TW. Hydrogen production with the PV-EL-FC system will be about 20 tonnes-day-1-km2 with an efficiency of 20%. Explicit calculations are given; these models could be scaled and digitized for individual countries.

The macro models do not consider the “duck curve” aspects of electric grid (EG) management caused by the integration of renewable sources into existing fossil-fueled grid infrastructures during the transition period. Hydrogen storage and “smart grids” are discussed in **Part 6**.

Part 3 – Electrochemistry of Water Electrolysis and Hydrogen Fuel Cells

The electrolysis (EL) of water, powered by solar PV panels, will produce hydrogen which is utilized in fuel cells (FC) to produce electricity for grids. Tutorial derivations of the equations for hydrogen production by water electrolysis and hydrogen consumption in fuel cells are given. These relations were used in **Part 2** for the PV-EL-FC models. Basic principles of OER, HER, HOR, ORR processes and catalytic activities are presented. PV-EL systems, with large reductions in PV electricity cost will make this method of hydrogen production more economical as it approaches $1.00 per kg by 2050.

 4

Large-scale EL-FC installations are currently limited by the availability of **critical/scarce** elements used in their electrodes and electrolytes. Their replacements by **earth-abundant** **materials** will be an essential development which are examined in **Part 4.**

With a basis in quantum mechanics, Density Functional Theory (DTF) is seen as an extremely important tool in (1) improving fundamental knowledge of electrocatalytic processes, (2) screening of earth-abundant materials, and (3) design and development of electrode structures for electrolyzer and fuel cell components. Among the replacement candidates for platinum group of metals (PGM) are the transition metals and carbon-based materials. In addition, metal-carbon compositions are also under development. Inter-laboratory collaborations between electro-catalytical theorists and experimentalists will expedite the development of components for electroyzers and fuel cells.

Part 4 – Critical Materials Limitations and Research in Earth-Abundant Elements

Using the annual world energy demand level of 500 EJ, estimates of PV-EL-FC component materials were determined by **Part 2** **“macro-models”** in relation to world annual production levels and reserves. Although PV-EL-FC systems have demonstrated mature technologies and commercial applications, they will be limited on a global scale by the availability of certain chemical elements within their **Part 4** **“micro”** components such as solar panels as well as electrolysis and fuel-cell electrolytes and electrodes. For example, the precious metal, silver in solar panels, and scarce elements in electrolyzers and fuel cells, including the platinum group of metals, must be replaced by earth-abundant elements. Research in materials for electrolyzers and fuel cells with **“nano-models,**’ is described earlier in **Part 3**. PV-EL-FC material and power limitations are also discussed.

Two current solar PV materials appear to be feasible at the 100 TW level. Crystalline silicon (20% efficient) installations can be expanded to global levels if silver contacts are replaced with copper and/or aluminum. It should be noted that these two metals will also be required in large quantities for electric grid systems. Conductors for these grids will consist, in part, of carbon-based materials. Additionally, amorphous silicon (10% efficient) will also become a prominent PV component. In its R&D stage, the perovskite sub-type chalcogenide, CZTS, (10-20% efficient) will be available in thin-film (1μm) form as an earth-abundant material, limited by its tin (non-earth-abundant) content, for 100 TW power production. It is emphasized that solar PV panels with a10% conversion efficiency will require twice the “solar farm” areas compared with the calculated silicon, 20% efficient, PV arrays in **Part 2** of this guide. Analyses of materials availability should be based on complete PV-EL-FC-EG systems.

In the transportation sector, PEM fuel cells containing 20-mg platinum electrode loadings per vehicle can power only about **5%** of new vehicles. As seen in **Part 3**, the activity and durability of PGM-free and metal-free catalysts, as applied to ORR processes in the PEMFC, remain inferior to those of the PGM. In addition, 20-kg lithium batteries can provide power to less than **2%** of new vehicles. These estimates are based on the annual world production of the elements. Increased implementation may require depletion of world reserves if replacements or alternatives are not available.

 5

Part 5 – Alternative Methods for Hydrogen Production

In addition to indirect electrolysis (EL) of water powered by solar photovoltaic (PV) panels, the direct interaction of solar radiation with water sources has been attempted with several methods. The photoelectrochemical (PEC) method produces reasonable rates of hydrogen and is potentially viable at the commercial level. Scaled PEC hydrogen production with critical and earth-abundant materials is estimated to be about 12 tonnes-day-1-km2 or **60%** of the production of PV-EL-FC systems. A statistical analysis of PEC cells with **critical** and **earth-abundant materials** is given, together with a tutorial in the Appendix. Density Functional Theory was seen to improve PEC performance, specifically by increasing photocurrents and hydrogen production rates, by factors of **2-10**. Examples of near-infrared (NIR) PEC cells exhibited photocurrents and hydrogen production rates which were comparable to their visible PEC cell counterparts.

The photocatalytic (PC) method was also reviewed. Samples of literature experimental results of cells with **critical materials** exhibited hydrogen production rates of approximately **5%** of those obtained from the PV-EL models described in **Part 2.** These rates for devices consisting of **earth-abundant materials** produced hydrogen at rates of only **1%** of the PV-EL models.

Currently, these methods remain in the research stage, unable for technical and economic reasons, to produce large quantities of hydrogen. PV-EL will likely remain as the best method for producing hydrogen until the tentative end of the “net-zero” transition period in 2050.

Part 6 – Three Views of Hydrogen

In addition to solar irradiance, hydrogen is an essential resource for variable-renewable-energy storage, and it is important to understand the characteristics of this medium. A common feature of these views is their interpretation in terms of economic/energy supply and demand.

As an **economic** commodity, the prices and quantities of hydrogen are determined by the supply and demand factors in this market. Unlike fossil fuels which are available in only a few countries, solar energy in generally available in many regions, making this source more secure than that provided by fossil fuels.

In **physical** terms, hydrogen may be produced in a PV-EL-FC system by the solar-powered electrolysis of water, and utilized by fuel cells to produce electricity for grids (EG). A world annual energy demand (output) of 500 EJ can ideally be produced by a power source of 15.9 TW. However, with an efficiency of 21%, the supply (input) energy is 2,375 EJ, and a capacity factor of 25% requires a supply (input) power of 300 TW. A likely minimum power is 100 TW.

The ratios of input/output power and energy for the WSG models of **Part 2** are **20:1** and **4.7:1** respectively. Electric grid **management** can be achieved with hydrogen storage and “smart grids” which will balance supply and demand for transitional “duck-curve” grids and future fully-renewable grids. It is also necessary that consumer demand be reduced and that daily needs be rescheduled.

 6

Part 7 – Requirements for Global Deployment

The fossil-fuel era will have lasted approximately **300 years**, from 1750-2050 either physically or economically, and the **transition** period from fossil fuels to renewables is expected to last (at least) **30** years, but likely will continue for a longer time span. Knowledge of renewable energy and climate models have been known for **200 years**. The period of 2020-2050 is seen to be the “net-zero CO2 emissions” window, while a longer time-frame to realize a complete transition to “net zero” and renewable energy sources will likely be necessary, possibly until the end of the 21st century. The “net-zero” scenario should be distinguished from the “100% renewable” case.

Many requirements are needed for global renewable energy, and few are summarized here:

* Commitment to environmental sustainability
* Workable transition plans
* Public-private entity involvement at regional, national, and municipal levels
* Natural resources for solar energy and hydrogen storage:

 Solar irradiance for (PV) power

 Water for (EL) hydrogen production

 Hydrogen storage facilities such as salt caverns for (FCs) and grid (EG) input power

 Land use in populated areas for solar (PV) panels and water electolyzers (EL)

 Scarce/critical chemical elements, primarily the platinum group

 Earth-abundant elements such as transition metals and carbon-based materials

* Communication (science and technology transfer) via journal, internet, and other means
* Education (K-12, university, trade associations)
* Research, development, production, and reclamation/recycling
* Commercialization
* Technical and economic viability
* Financial resources (majority private and public)

Reviews of literature research results discussed in **Part 4** showed catalytic properties of **critical** elements are superior to those of **earth-abundant** materials in electrolyzers and fuel cells. However, hydrogen production levels of PEC devices were found in **Part 5** to be similar for both types of materials. These comparisons suggest that earth-abundant materials can replace the critical elements currently used by PV-EL-FC systems for large-scale installations as described in the **Part 2** models. Although these results are encouraging, challenging improvements in performance, durability, and scalability will be required for water electrolyzers and hydrogen fuel cells to produce the minimum necessary global levels of 100 TW power and 500 EJ energy.

This transition may take place during the remainder of this century rather than the 2050 limit.

Part 8 – Policies and Strategies for Solar Implementation

The following topics are addressed in Part 8:

 Policy Statement

 World Solar Guide Systems and Other Systems

 Strategies

 Transition Plans (Spoof and Real)

 A Pedagogical Note and Proposed Educational Curriculum Outline

 7

Part 9 Commercialization of Solar Photovoltaic Panels, Electrolyzers, and Fuel Cells

The ultimate purpose of research and development is the commercialization and installation of renewable sources of energy on a global scale which will result in the long-term sustainability of earth’s ecosphere. A concluding statement regarding these efforts described in **Part 9** is given here as follows with the “color code” used in **Part 4.** This “color code” may be considered as a “traffic light.”

 Summary of projections for global “net-zero” or “100% renewables” installations.

|  |  |
| --- | --- |
| Commitments andTransition Plans | Some countries are well advanced in renewable energy sources.Many countries have gaps in their NDC commitments and transition plans. |
| Cost estimatesand financial resources | $130-$140 trillion over 30 years, $4.3-$4.7 trillion annuallyvs. $5 trillion for annual fossil fuel subsidiesOut of $2.5 trillion current investment in energy only a fraction is for renewables.  |
| Systems/Components | PV/cells/panels | EL/electrodes/electrolytes | FC/electrodes/electrolytes |
| Minimum global power levels with earth-abundant materials | 100 TW | 100 TW | 10 TW  |
| Required growth ratesfor global installations | 17% | 53% | 33% |
| Overall assessment | Uncertainty concerning “net-zero,” 1.5 C limit, and 100% renewable energy installations by 2050.Temperature may reach 2.7 C, and renewable funding must increase substantially. |

 8

Final Summary and Conclusions

An overall summary and set of conclusions of the **World Solar Guide** can be expressed in five segments:

1. Commitment and Transition

With “Nationally Determined Contributions” having been made by some countries to replace fossil fuels with renewables, transition plans must be developed and implemented. However, these commitments are at the present time not “universally” accepted as many countries have not made these commitments, and a few are even increasing their production of coal. While “clean” coal may contain less sulfur, the fact remains that C + O2 🡪 CO2. Methane is oxidized in the reaction, CH4 + O2 🡪 CO2 + H2O. In addition, CH4 is a stronger absorber of the Earth’s infrared radiation than CO2 by a factor 0f 30 as it contains more quantized vibrational modes. Coal, oil, and natural gas will have further physical or economic lifetimes of only about 50 years. Utility companies are currently investing more in new renewable sources of energy than in fossil fuels.

The negotiation of the Paris Accord covered the period of 1988-2015, or 27 years. During this time, the earth’s temperature rose approximately 1.0 C or two-thirds of the limitation goal, 1.5 C, meaning that only 0.5 C remained as an acceptable increase by 2050. The fossil era will have lasted 300 years, from 1750-2050, and the transition period of only 30 years, from 2020-2050 as viewed by some organizations may not be realistic.

This transition should be an active demonstration of the commitment to global sustainability. Both public and private contributions at national, regional, and local levels will be necessary. Some small countries will successfully implement this transition within the next few years. Similarly, world-wide municipalities have already taken significant steps with installations of renewable sources. Some high-energy countries are still deficient in their commitments.

2. Science and Technology

Renewables take many forms, and solar energy, specifically, photovoltaic, will likely become the most prominent. The world’s “energy transition problem” is essentially a “materials problem.” Although a few minutes of solar radiation could power the earth’s needs for a year, many of the chemical elements within the earth’s crust required to capture, convert, store, and utilize this energy are critically limited.

 Certain elements, such as silver for solar-panel electrical contacts, and the platinum group of metals for electrolyzer and fuel-cell catalysts will not be available on a global scale and will be prohibitively expensive on small scales. These elements used in the system components must be replaced by earth-abundant sources.

 9

Several thousand scientific papers in the areas of solar power, electrolyzers, fuel cells, and related systems for renewable energy are published annually. These papers typically show 100-5,000 views, often with 100 citations. Researchers are aware of critical-material limitations and are actively experimenting with earth-abundant replacements, including the transition metals, (not to be confused with the fossil-renewable transition) and carbon-based materials. Scaling centimeter-sized laboratory samples to meter-sized solar PV panels, a factor of **10 thousand**, will be a daunting task.

Solar power is variable in time and space, meaning that even the locations with the highest irradiance receive this power only about five to six hours per day for direct PV electric power and EL hydrogen production. The remainder of this daily period will require about five times of the daily requirement for hydrogen storage and FC utilization. The total land area for the PV-EL-FC installations will be about 20% the size of the Sahara Desert which is less than 0.5% of the earth’s land mass. Several scalable models were presented which are intended to provide power to electric grids and hydrogen for other sectors.

3. Economics and Finance

The proposed economic benefits of renewables during the transition period such as increased net-energy employment and GDP growth have been well documented. Individuals will experience lower utility bills, and nations will see energy independence and security. The avoidance of climate impacts will also result in more stable agricultural production and a sustainable biosphere. Reduced sea-level rises will avoid unnecessary coastal re-developments.

There is a strong correlation between economic growth and energy utilization; this growth should be re-analyzed after the transition period and into the earth-sustainability period.

Economic growth must be viewed through the lens of environmental sustainability. Renewable energy has been shown to benefit both economic growth and environmental sustainability.

Financing the transition will require both public and private sources, with the latter providing most of this funding. The total world cost over a period of 30 years has been estimated by “pathways” to be in the range of about $100-$130 trillion or $3-$4 trillion per year which is less than the current annual world fossil-fuel subsidies of $5T.

 10

4. A Note to Readers

This website is intended as a resource for researchers, developers, and advocates of renewable energy. It is also considered to be an educational tool for teachers and students at the high school and college/university/trade levels. Although many portions of the guide are suitable for general readers, several scientific and technological concepts are also presented. In this regard, teachers may find sections appropriate as lecture materials. In addition, **Parts 1-5 and 8**, contain tutorials for student reviews. For example, the **Part 1** Appendix includes notes on the scientists who contributed to the laws of physics which led to Maxwells equations. The detailed derivation of these equations includes portions which are often omitted in textbooks as “details” or “it can be shown” segments. The only portion not included in detail here was an “integration by parts of a cubic term” which fortunately became available from an online calculus tool.

In addition to the photon-physics concepts, important for solar-cell background knowledge, basic electrochemistry principles are included in the **Part 3** Appendix. These concepts are necessary for the understanding of electrolysis and fuel cell devices. **Part 5** is a section on alternative methods of hydrogen production. Its **Appendix** gives an analysis of experimental results obtained from literature sources. From a literature review, an interesting result found that a linear relation existed between solar-to-hydrogen (STH) conversion efficiency and hydrogen production when **critical** materials were used in the photoelectrochemical (PEC) cells. A derivation of the “least squares method” is given from which the “correlation coefficient” and “coefficient of determination” were determined. In contrast to this result, no such linear relation was found between these variables when other elements known as **“earth-abundant”** materials were used as components in PEC cells. Thus, the mathematically abstract notion of “least squares” was related to laboratory experimental techniques and statistical analyses, concepts which should be appreciated by students.

**Part 7** presents suggestions for developing an educational path towards a career in renewable energy. Clearly, this field is interdisciplinary in nature, and it should be seen that a formal education is limited in its scope. Typical college/university majors might include, Chemistry, Physics, or one of the Engineering Departments such as Electrical, Chemical, or Materials. All these majors would include similar curricula during the first two years. Later years will offer opportunities for specialization. It has become known that Density Functional Theory, a derivative of Quantum Mechanics, is extremely important not only in understanding basics concepts of electrochemical activities in electrolyzers and fuel cells, but also in screening new materials for development. It should be noted that theorists and experimentalists do not often inhabit the same scientific space as it is difficult to become competent in both endeavors. However, as the “Scientific Principle” requires testing theoretical models, collaboration between these parties is necessary. Literature searches in renewable energy revealed that many research papers were prepared by several authors, often 10-20 in number. Such papers exemplified theoretical-experimental collaborations.

As **critical** materials such as platinum are insufficient in quantity for global installations, **earth-abundant** elements will be required expeditiously for these systems. The “energy crisis” is a “materials crisis.” Rewarding careers await those who prepare to address these challenges.

 11

 5. Postscript

“Net-zero CO2 emissions by 2050” p**athways** are predicted to result with remaining fossil fuels still in use. These pathways do not recommend adequate energy production and storage levels by 2050 nor after this date. Some “Net-zero CO2 emissions by 2050” pathways do not provide specific plans for adequate energy production.

A certain irony can be attributed to the **300-year** (1750-2050) fossil-fuel era as it will have nearly coincided with the **200 years** in which basic chemistry, physics, electrochemistry, renewable energy principles, and climate models have existed.

**World-Solar-Guide** is also an implicit commentary on the likely post-2020-2050 era as well as the current **transition period** which appears to be unduly short. The achievement of “Net-zero” and adequate renewable energy production will likely require a period longer than a generation.

This Guide is not a “how-to manual” for developing a complete global renewable-energy system, but rather an exhortation to expeditiously develop **new earth-abundant materials and processes** in the production of effective PV-EL-FC-EG components and systems. It is hoped that this Guide will be useful for students, faculty, researchers, and developers during the current transition period and for the next era which must become both life-sustaining and indefinite.

Although the “energy crisis” is, in fact, a “materials crisis,” the ultimate tasks range far beyond these limits. At stake is the biosphere itself, the flora and fauna kingdom. Preceded by astronomical and geological time scales of 13 & 5 billion years ago respectively, the biological period on Earth began less than a billion years ago, with fossil products having an age of about **300 million years.** These products in the form of fossil fuels have largely been consumed in only **300 years**, a period less than 5% of recorded history.

**Sustaining this biosphere** requires maintaining the plant and animal species, most of which were lost in the asteroid impact 70 million years ago. These losses continue today. In addition, water resources, salt and fresh, must be managed more effectively. The rise in sea-water temperature has already produced a negative impact on species reproductive rates. The loss of forests, which began in Europe and other regions more than a millennium ago and continues today along the Amazon, should be reversed rather than abated. Agricultural practices should be modified, to reduce or eliminate artificial nutrients, keeping these areas productive rather than turning them into “biofuel” farms.

Many “net-zero pathways” include **population** increases in their models. It would seem, however, that the world human population should not only be limited but decreased as its destructive consumptive practices continue, not just in energy but in all resources, at unsustainable levels. The Malthusian Population Theory of 1798 may not be totally valid, but world resource limits, in addition to food, still exist.

Several “Pathways,” “Roadmaps,” and “Guides” have already been written for the global development of these concepts. Their reviews and **immediate implementation** are now crucial.