**World Solar Guide** 1

 **Part 7**

 **Requirements for Global Deployment of Solar Energy and Storage**

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

jon.canaday@world-solar-guide.com



 Image from greentechmedia.com

 Copyright © Jon D. Canaday, 2023

 2

 **World Solar Guide**

 **Part 7**

 **Requirements for Global Deployment for Solar Energy and Storage**

Table of Contents Page

1. Introduction 3

2. Commitment to Environmental Sustainability 3

3. Transition Plans 4

4. Organizations Engaged in Renewable Energy 7

5. Natural Resources 8

 5.1 Solar Irradiance 9

 5.2 Water for Hydrogen Production 9

 5.3 Hydrogen Storage Facilities 9

 5.4 Land Use for Solar Photovoltaic Panels 9

 5.5 Chemical Elements 10

 5.5.1 Critical Elements 10

 5.5.2 Earth-Abundant Elements 10

6. Education 11

7. Research and Development 12

8. Financial Resources 13

9. Economic Viability 14

10. Conclusions 15

11. References 17

 3

 **World Solar Guide**

 **Part 7**

 **Requirements for Solar Energy and Storage**

1. Introduction

The fossil fuel era will have lasted approximately **300 years**, from 1750-2050, less than 5% of recorded history. This period may be compared with the time since the beginning of fossil-fuel formation, **300 million years**, and an even shorter time relative to the geological period, an excess of **1 billion years**. Although this era has contributed to the development of civilization and its economies, it has brought the earth to point of serious global atmospheric warming, currently more than 1 C since the beginning of the Industrial Revolution around 1750. Although CO2 is a natural product of the earth’s carbon cycle which maintains the atmospheric average temperature of 20 C, **excess** **emissions** due to anthropogenic activities have increased this content from 300 ppm to more than 400 ppm. These molecules have quantized absorption bands in the infrared region of the Planck radiation spectrum which correspond to the earth’s temperature. Hence, increased CO2 concentrations and absorption of this radiation lead to higher atmospheric temperatures. National commitments will form the bases for necessary transition plans. The World Solar Guide has addressed these issues through its advocacy of replacing fossil fuels with renewables, primarily solar energy with hydrogen storage by 2050. The “macro” models and systems for achieving this goal consist of solar photovoltaic (PV), water electrolysis (EL), and hydrogen fuel cells (FC), PV-EL-FC, as described initially in **Parts 1 & 2** of this guide. In **Parts 3-5**, analyses of components and materials limitations at the “micro” and “nano” levels are presented. A portion of these findings are summarized here in **Part 7.**

2. Commitment

The primary requirement for implementing the transition from fossil fuels to renewable energy is the **commitment** to developing a sustainable environment rather than just a realization of its necessity. These commitments, known as Nationally Determined Contributions (NDC), were first obtained by the International Panel on Climate Change (IPCC) [1] in 2015. While many countries made initial commitments, there is currently a gap in these contributions by 140 countries who are responsible for 90% of the world’s CO2 emissions [2]. This gap will result in an atmospheric warming of 2.7 C (4.9 F) by 2100 rather than the IPCC goal of 1.5 C (2.7 F) in 2050. Other sites such as Carbon Tracker [3] tracks financial investments of energy sources. In addition, Climate Action Tracker [4] monitors governments responses to the Paris Accords and follows net-zero commitments.

 4

3. Transition Plans

Many examples of transition plans appear online [5]. Recurring themes among these plans are the integration and sustainability of their elements into a coherent plan.

 

 Image from Frontiers in Energy Research [5]

This site seeks sustainability in the following areas as shown in Table 1:

 Table 1. Sustainability in transition plans.

**Integration and Sustainability**

Technology

Environment

Economy

Social

Political and Institutional

 5

Planning for these transitions will likely be the most difficult task among the requirements for global deployment of renewable systems, one in which the avoidance of economic and social dislocations will be mandatory. Transition plans for **“net-zero by 2050”** can be divided into seven types [6] in Table 2:

 Table 2. Types of transition plans.

**Types of “net-zero by 2050” Transition Plans**

Environmental/Nature

Utility/Technology Companies

Finance/Investment Companies

Educational Institutions

Associations

Governments

Intergovernmental/International Organizations

It should be noted that “net-zero by 2050” does not necessarily coincide with “100% replacement of fossil fuels with renewable energy sources” as the “net-zero” plans may recommend a range of about 70-100% renewables. A few of these plans are listed in Table 3.

Detailed commentaries and evaluations of these transition plans are beyond the scope of this Guide. However, a few points can be given. First, the International Energy Agency and other “pathways” discussed in **Part 1** stated that a portion of the energy mix for “net-zero by 2050” will allow fossil fuels. Different guides advocated for 100% renewables by this date. Second,

[6], listed in Table 1, claimed that financial institutions should not fund the expansion of this fossil-fuel component during the transition period. It can be seen in this table that utility-company and financial-institution types form the largest numbers of plans. The table is not a complete list of plans, but it should represent a reasonable cross-section. Third, transition plans, developed for specific purposes, should contain detailed descriptions of the plan elements, including goals, strategies, and time-lines. Perhaps, the “ultimate plan” would be a

“plan of plans.” A simple example of such a plan is given in **Part 8**.

 6

Table 3. Transition plans and websites [6].

|  |  |
| --- | --- |
| **Transition Plans**  | **Websites** |
| Environment/NatureWorld Wildlife FundSierra Club | [www.wwf.org](http://www.wwf.org) [www.sierraclub.org](http://www.sierraclub.org)  |
| Utility/Technology CompaniesEquinorConocoPhillipsTrane TechnologiesNational Grid GroupBritish Petroleum Southern CompanyShell GlobalExxon Mobile | [www.equinor.com](http://www.equinor.com) [www.conocophillips.com](http://www.conocophillips.com) [www.tranetechnologies.com](http://www.tranetechnologies.com) [www.nationalgrid.org](http://www.nationalgrid.org) [www.bp.com](http://www.bp.com) [www.southerncompany.com](http://www.southerncompany.com) [www.shell.com](http://www.shell.com) [www.corporateexxonmobile.com](http://www.corporateexxonmobile.com)  |
| Finance/Investment/Consulting CompaniesMcKinsey & CompanyCDPCitigroupTransform to Net ZeroBlackrockEnvironmental Defense FundThe Phoenix GroupBloombergCleanTechnicaGlasgow Financial Alliance for Net Zero | [www.mckinsey.com](http://www.mckinsey.com) [www.cdp.net](http://www.cdp.net) [www.citigroup.com](http://www.citigroup.com) [www.transformtonetzero.com](http://www.transformtonetzero.com) [www.blackrock.com](http://www.blackrock.com) [www.business.edf.org](http://www.business.edf.org) [www.thephoenixgroup.com](http://www.thephoenixgroup.com) [www.bloomberg.com](http://www.bloomberg.com) [www.cleantechnica.com](http://www.cleantechnica.com) [www.gfanzero.com](http://www.gfanzero.com)  |
| Educational InstitutionsNational Academies of ScienceHow to write a net zero transition planLondon School of Economics and Policy Science | [www.nationalacademies.org](http://www.nationalacademies.org) [www.rypeoffice.com](http://www.rypeoffice.com) [www.lse.ac.uk](http://www.lse.ac.uk)  |
| Agencies/AssociationsInternational Energy AgencyInternational Renewable Energy Agency  | [www.iea.org](http://www.iea.org) [www.irena.org](http://www.irena.org)  |
| GovernmentsUS Department of Energy The Whitehouse | [www.doe.gov](http://www.doe.gov)[www.whitehouse.gov](http://www.whitehouse.gov)  |
| Intergovernmental/International OrganizationsUnited NationsInternational Panel on Climate ChangeEuropean Commission | [www.un.org](http://www.un.org)[www.ipcc.org](http://www.ipcc.org) [www.climate.ec.europa.eu](http://www.climate.ec.europa.eu)  |

The Sierra Club reported [7] on 77 electric utility companies in the US owning one-half of all remaining coal and natural gas generation to determine whether they are successfully preparing for the clean-energy transition. It was found that the aggregate score for these transition plans was 26 out of 100 points. Major results of the report concerning utility plans for 2030 include:

Only 35% of coal usage will be retired.

Only 30% of fossil fuels will be replaced by renewables.

53 GW of new gas-powered plants will be built.

 7

The **World Solar Guide (WSG)** does not develop specific transition plans. However, the Guide provides the following unique resources which are considered to have merit in these constructions of Table 4:

 Table 4. WSG resources for transition plans.

**Unique Features of the World Solar Guide**

Quantitative PV-EL-FC models at macro, micro, and nano levels

Models can be scaled to off-grid (“roof-top”) municipal, national,

 regional, world sizes

Evaluations of system components with **critical** and **earth-**

 **abundant** materials

Determinations of material and electric power limitations

Analyses of earth’s natural resources for renewable energy

Reviews of scientific literature for solar PV, electrolyzer, and

 fuel cell developments with earth-abundant materials

Energy management of supply/input and demand/output

General educational sections

Tutorial modules for teachers and students of renewable energy

4. Organizations Engaged in Renewable Energy

A useful list of about 150 organizations engaged in renewable energy has been posted [8]. The list in Table 5 includes organizations related to markets, policy, and investment, mostly excluding those whose main-focus is technical research and development:

 Table 5. Organizations in renewable energy.

**Organizational Types Engaged in Renewable Energy**

Market Facilitation

International Networks and Partnerships

Advocacy an Educational Groups

National Governmental Agencies

Foundations

Organizational Initiatives Supporting Corporate use of

 Renewable Energy

Research Centers

Universities with Degree-Granting Programs

**Parts 1-6** of the World Solar Guide cites literature references for research papers in the areas of solar photovoltaic cells, water electrolysis, hydrogen fuel cells, and smart electrical grids. Section 7 of **Part 7** also summarizes R&D activities for these systems. **Part 9** gives an illustration of the R&D spectrum as it relates to universities, governments, and industries.

 8

5. Natural Resources

Natural resources for the production and storage of solar energy range in scale from an over-abundance of solar radiation to limitations imposed by certain critical chemical elements. These natural resources describe in the **World Solar Guide** will be discussed briefly in this section and are summarized in Table 6. The color code (“traffic light”) for these resources is given in **Part 4** of this guide.

Table 6. Abundances of natural resources.

|  |  |  |
| --- | --- | --- |
|  **Natural Resource** | **WSG Reference** |  **Abundance and Characteristics** |
| 5.1 Solar irradiance for  photovoltaic power of  electrolysis | Parts 1, 2 | The earth receives 10,000 timesits irradiance needs for power.Large geographical variations. More feasible in mid-latitudes, 30 N – 30 S.Solar power is variable and requires storagefor “night-time” hours. |
| 5.2 Water for electrolysis  to produce hydrogen   | Parts 2, 3 | Closed system for PV-EL-FC grid useOpen system for hydrogen productionSea water requires desalination or direct electrolysis |
| 5.3 Hydrogen storage | Parts 2, 6 | Closed system for PV-EL-FC grid useOpen system for hydrogen production.Large global numbers of existing and  potential salt-caverns. Gas pipelines for distribution.Large geographical variations. |
| 5.4 Land use for PV panels | Part 2 | Limited by irradiance requirements, terrain, population density.May require 5-10 % of country land area for  solar use with > 2,000 hours/year |
| 5.5.1 Critical/scarce chemical elements  | Part 4 | Critical limits for platinum group, precious metals, some rare earths.Will be insufficient for global scale. |
| 5.5.2 Earth-abundant chemical elements  | Part 4 | Earth-abundant elements for PV-EL-FC systems  may exhibit less activity, efficiency, and  durability than critical elements.Will require extensive R&D, production, and  reclamation.Required for global hydrogen production  and fuel-cell utilization by 2050. |

 9

5.1 Solar Irradiance

Regional solar-irradiance maps are shown in **Part 1.** An irradiance level of 2,000 hours per year is required for a reasonable production of PV power. In regions such as Northern Europe with low irradiance levels it may be necessary to import electricity and/or hydrogen.

5.2 Water

For the PV-EL-FC models discussed in **Part 2** of the guide, both water for electrolysis and hydrogen fuel used in the fuel cell, are contained in closed, re-usable systems. In the case of direct PV-EL hydrogen production, water is required in the stoichiometric ratio of 9:1. The actual ratio will be higher as shown in **Part 2.** This water is not lost, as is becomes a product of fuel-cell electricity production, but it is not directly recovered in a closed system.

5.3 Hydrogen Storage

Maps of existing and potential salt caverns are shown in **Part 2**

5.4 Land Use for Photovoltaic Panels

It can be recalled from **Part** 2 that Europe has a higher population density than that of China,

and that the use of land for PV-EL-FC systems was evaluated. Here, the PV areas, PV1, PV2, and PV3 were determined. These areas can be scaled down to country levels based on the assumed global annual energy use of 500 EJ.

As examples of areas with high solar irradiance levels (>2,000 hours per year), consider three countries in Southern Europe, Portugal, Spain, and Italy. The solar PV areas can be estimated by calculating these countries’ annual energy use as a percentage of the global consumption as shown in Table 7.

Table 7. Examples of land requirements to produce solar PV power.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Annual energy consumption(TWh)  | Global1.39x105 | Portugal300 | Spain1,800 | Italy2,200 |
| % of global energy consumption | ---------- | 0.22 | 1.3 | 1.6 |
| PV1 area (km2), daytime grid | 2.85x105 | 627 | 3,700 | 4,560 |
| PV2 area (km2), nighttime grid | 1.40x106 | 3080 | 18,200 | 22,400 |
| PV3 area (km2), hydrogen production | 2.07x105 | 455 | 2,700 | 3,300 |
| PVtotal area (km2) | 1.87x106 | 4,100 | 24,300 | 29,900 |
| Land area (km2) | 149x106 | 92x103 | 506x103 | 301x103 |
| PVtotal area as % of world land mass area and country areas | 1.3 | 4.5 | 4.8 | 9.9 |

From Table 7, it is apparent that these PV areas in Southern Europe will require significant land areas (5-10%) to supply their own energy needs. If these countries export electric power or hydrogen, for example to Northern Europe, even larger areas will be needed.

 10

5.5 Abundance of Chemical Elements

**Part 4** discusses the critical material limitations of PV-EL-FC systems. Solar PV power on a global level will require the replacement of many **critical** elements such as the platinum group of metals with **earth-abundant** elements. Although these elements are less costly, they also may exhibit less catalytic activity, less efficiency, and poorer chemical stability than their counter parts. Nevertheless, these elements, with “catalytic engineering” development will become the building blocks for global installations of electolyzer and fuel cell systems.

 11

6. Education

The **World Solar Guide** offers subject areas in each segment as tutorial resources for instructors and students of renewable energy in Table 8. Universities and degree-granting programs are also listed [7].

Table 8. Segments and subjects in the World Solar Guide.

|  |  |
| --- | --- |
| **Segments** | **Subjects** |
| Part 1The Case for Solar Photovoltaic Energy  | Earth in a Planetary Context, Energy Supplies: Fossil, Nuclear, Renewable; Energy Demand, Environmental Factors, Economic Considerations, Projections of Energy Supply and Demand, Plan for Global PV, Appendix Tutorials: Arrhenius Model, Maxwell Equations, Planck Radiation Law, Einstein Effect, Physics and Technology of Solar Cells, Units, Measures, Conversion Factors, |
| Part 2Storage Requirements forVariable Solar Energy | Climate Imperative, Solar Energy, Variable Renewable Energy, Energy Storage, Water Resources, Hydrogen Storage, Working Systems and Simulations, Solar Energy Models,[Four Energy Regions][Environmental-Economic Factors] China, US, Europe-E5, India[Land Use] Applications, Projections, Pathways, ModelsCost Summary |
| Part 3Electrochemistry of Water Electrolyzers and Hydrogen Fuel Cells | Electrolyzers: Processes, Types, R&DFuel Cells: Processes, Types, R&DAppendix Tutorials: Chronology, Basic Principles, Density Functional Theory |
| Part 4Critical Materials Limits andResearch in Earth-Abundant Elements | Methodology, General Chemical Abundances, PV Devices, Electrolyzers, Fuel Cells, Electric Grids, Environmental Considerations,Materials-Devices Summaries, Growth Rates, Country/Region Viabilities |
| Part 5Alternative Methods forHydrogen Production | Alternative Methods: Photoelectrochemical (Density Functional Theory), Photocatalytic, Photo-Thermo-Chemical, Photo-Biological, Solar-Thermal-Chemical; Appendix Tutorials: Scaling, Conversion Factors, Statistical Analysis and Least Squares Method |
| Part 6Three Views of Hydrogen | Economic (Supply and Demand)Physical (Supply and Demand)Management (Supply and Demand) |
| Part 7Requirements for Global DeploymentOf Solar Energy and Storage | Commitment to Environmental Sustainability, Transition Plans, Entities, Natural Resources: Solar Irradiance, Water, Hydrogen, Land,Chemical Elements (Critical, Earth-Abundant); Education, Research, Development, Production, Reclamation, Commercialization, Financial Resources, Economic Viability  |
| Part 8Policies and Strategies forSolar Implementation | Policy Statement, **World Solar Guide** **Systems** and Other Systems,Strategies, Economic Growth, Environmental Sustainability, RenewableEnergy, Energy Transitions in the US (a spoof), Energy Transition Plans (Employment, Example), Pedagogical Note and Proposed Educational Curriculum |
| Part 9Commercialization of Solar Panels,Electrolyzers, and Fuel Cells | Projections and Limitations: Definitions of Electrical Power and PowerLimitations, Global Power Needs, Electric Power Limitations, Costs, Growth Rates; Silos vs. Spectra; Manufacturers |
| Part 10Summaries | Segment Summaries, Note to Readers, Postscript |

 12

7. Research and Development

Literature research and development activities were cited in **Parts 1-6** of the World Solar Guide. Portions of these results are outlined in Table 9.

Table 9. Summary of research and development activities.

|  |  |
| --- | --- |
| **Segment** | **Research and Development (World Solar Guide and Literature References)** |
| Part 1Photovoltaic, (PV) cells | US DOE-NREL reported efficiencies in the range of 10-40% for multi-junction, single-junction, crystalline Si, thin-film, and emerging-technology cells |
| Part 2Hydrogen storagePV-EL-FC models | **World Solar Guide** models – 4 largest energy regions analyzed China, US, Europe-E5, India Small-scale PV-EL-FC working models, simulations reported Hydrogen import/export countries reportedGlobal Model Input/Supply Output/DemandEnergy 2,376 EJ-yr-1   500 EJ-yr-1 Hydrogen 12,575 M tonnes-yr-1 |
| Part 3Electrochemistry |  Anode CathodeElectrolyzer (EL) OER HER Earth-abundant materials reported Fuel Cell (FC) HOR ORR Earth-abundant materials reported  |
| Part 4Critical elementsEarth-abundant Elements | PV: some perovskites limited, chalcogenides abundant, silver limitedEL and FC: Ir, Pt, extremely limited; La, Y moderately limited Transition metals (Fe, Cr, Ni, Mo, Co) generally abundantPEMFCs (Pt electrodes): only 5% of new vehiclesEVs (Li batteries): only 2% of new vehiclesElectric power limitations were determined for components with critical and abundant elements |
| Part 5Alternative methods of hydrogen production | For the photoelectrochemical (PEC) method, wired and unassisted cells, critical and earth-abundant materials, produced hydrogen comparable to the conventional PV-ELmethod of 20 tonnes-day-1-km-2. The photocatalytic (PC) method results in 2 tonnes-day-1-km-2 with critical materials and 0.2 tonnes-day-1-km-2 with earth-abundant materials.Density functional theory: dopant and heterojunctions increased catalytic activity photocurrents and hydrogen production increased |
| Part 6Three views of hydrogen | Hydrogen as a commodity, physical substance, and grid management toolis considered as supply/demand elements.Smart grids reported. |

R&D efforts continue for the traditional method of hydrogen production, electrolysis of water, as seen in **Part 3** of this guide. The critical elements currently used in PV-EL-FC systems and their necessary replacements by earth-abundant materials are considered in **Part 4**. Other methods of producing hydrogen including photoelectrochemical, photocatalytic, and photobiological, and hybrid systems a were summarized in **Part 5** where it was concluded that these methods will remain in the research stage as uneconomical during the foreseeable future. **Part 9** looks at the spectrum of R&D activities leading to the commercialization of PV-EL-FC systems as contributed by university, government, and industrial organizations.

 13

8. Financial Resources

The Sierra Club [9] reported results from Profundo [10], a financial services research firm in the Netherlands. This research addressed lending and bond underwriting transactions by the world’s 60 largest commercial banks to 377 companies operating in the global energy sector (coal, oil & gas, electricity, and renewable energy) for the period of 2016 to 2022. These companies represent 75% of the world production volume for all activities related to fossil fuels and renewable energy. It was found that of the $2.5 trillion in these transactions, only $178 billion, or 7%, was related to renewable sources such as wind and solar.

By contrast, a related report by BloombergNEF [11] stated that 80% of energy investments should be for the area of renewables by 2030 to reach climate goals. The Sierra Club claimed that these results called into question pledges from the industry-led Glasgow Financial Alliance for Net Zero (GFANZ) who commissioned the research. The Sierra Club also claimed that energy sources such as biomass, nuclear, blue hydrogen and carbon capture and storage should not be included in calculating investments in clean energy.

The World Energy Forum reported [12], from a Bloomberg source, that $1.11 trillion was expended on fossil fuels in 2022. In addition, this amount, $1.11 trillion was spent on “Energy Transition Investment (ETI), with $550 billion going towards the energy supply side and $561 billion for energy demand. Within the ETI, $495 was invested in renewables, wind, solar, biofuels, and others.

 14

9. Economic Viability

It is well known that energy availability is a primary factor in economic growth. However, fossil fuels as an energy source are responsible for the anthropogenic increases in atmospheric CO2 emissions (CH4 + 2O2 🡪 CO2 + 2H2O) leading to the trapping of the earth’s infrared ration and higher temperatures. Renewable sources, on the other hand, provide for this growth while also providing environmental sustainability over the long term. A summary list of economic benefits

derived from renewable energy is given below [13] in Table 10:

 Table 10. Economic benefits of renewable energy.

**Economic Viability**

1. Harnessing Renewable Energy: A Boon for Economic Growth

 The Rise of Renewable Energy

 Benefits of Renewable Energy for Economic Growth

 Job Growth

 Energy Independence

 Cost Savings

 Reduced Environmental Impact

2. How Promoting Renewable Energy Powers Economic Prosperity

 Reducing energy costs

 Energy Independence

 Environmental Stability

 Technical Innovation

3, Renewable Energy Fueling Economic Expansion and Job Creation

 Renewable Energy – A Growth Industry

 Economic Expansion

 Local Investment

 Increased Tax Revenues

4. The Surprising Economic Gains Driven by Embracing Renewables

 The Shift Towards Renewable Energy

 Cost-Effectiveness

 Health and Environmental Benefits

5. Unveiling the Advantages of Embracing Renewable Energy

 Cost Savings

 Long-Term Stability

 Business Opportunities

 Job Creation

 Revenue Streaming

It was reported [14] that renewables increased from

1.22 TW in 2010 to 3.37 TW in 2022 at an annual growth rate of 8.8%. Increasing this installation to 100 TW by 2050 will require a growth rate of 12.9%.

 15

10. Summary and Conclusions

The IPCC Paris Agreement resulted in national commitments by 190 countries. However, deficiencies in these commitments by 140 countries, including all the G20 nations, will not lead to a global-warming cap of 1.5 C (2.7 F) by 2050. If these deficiencies continue, an increase in this temperature of 2.7 C (4.9 F) can be expected by 2100. In the US, electric utility companies most invested in coal and gas power plan minimal reductions in the use of coal and minimal replacements of fossil-fuel use with renewables by 2030. Major expansion of gas-powered plants is planned.

The transition concept of “net-zero CO2 emissions by 2050” allows for significant levels of fossil-fuels production. The total replacement of these fuels by renewable energy sources may occur after 2050.

Diverse organizations are presently engaged in developing renewable resources. These organizations may be considered as global resources.

The earth receives an over-abundance of solar irradiance and an abundance of water for electrolysis to produce hydrogen for electric-grid and chemical applications. While current systems are limited by critical elements such as silver and platinum, global installations will necessitate the development of earth-abundant materials as discussed in **Part 4**. Certain countries, in Southern Europe, for example, with substantial solar irradiation (> 2,000 hours per year) will require significant land areas (5-10%) for their own internal use. Those countries who elect to export electric power and/or hydrogen will require even larger land allocations.

The primary purpose of the **World Solar Guide** is to provide a resource for developers engaged in the installation of a 100% solar-hydrogen-storage-utilization energy system by 2050. This resource includes technical, financial, and time-line analyses on a global scale. Elements of this resource are presented throughout the Guide with specific data shown in the commercialization aspects of **Part 9**. A secondary purpose of this Guide is to offer a pedagogical/tutorial approach for teachers and students of renewable energy, particularly PV-EL-FC systems. Many of these concepts are suitable for learning at the high school and college/university levels. Research areas at the graduate-school and professional levels are also described throughout the Guide.

Research activities, particularly as they relate to the development of earth-abundant materials for components in PV-EL-FC systems were considered both from analyses by the World Solar Guide and from literature references. The required development of components with earth-abundant materials appears to be feasible.

 16

The overall transition cost, considered in **Part 9**, was estimated to be in the range of

$130-140 trillion over 30 years. Current investments in renewables are substantially inadequate.

The economic viability of the replacement of fossil fuels by renewable sources has been

well document elsewhere, with the benefits summarized in this segment.

A quantitative assessment of the global prospects for transition results by 2050 is given in **Part 9**

the World Solar Guide. Although the necessary technology requirements appear to be manageable, the installation growth rates for PV-EL-FC systems will be challenging, due in no small part to the current low level of financial investments in renewable sources. In addition, there is a major gap in national commitments by most of the original signatories to limiting the atmospheric temperature increase to 1.5 C. Thus, a large degree of uncertainty surrounds these prospects for 2050 at the present time.

 17

11. References

1. [www.unfccc.int/process-and-meetings/the-paris-agreement/2015](http://www.unfccc.int/process-and-meetings/the-paris-agreement/2015)

2. [www.newclimate.org/](http://www.newclimate.org/)

3. [www.carbontracker.org/](http://www.carbontracker.org/)

4. [www.climateactiontracker.org/](http://www.climateactiontracker.org/)

5. Kabeyi, M. J. B., and Olanrewaju, O. A., Sustainable Energy Transition for Renewable and

 Low Carbon Electricity Generation and Supply, Frontiers Energy Research, 9, 2022.

6. [www.cleantechnica.org/](http://www.cleantechnica.org/)

7. [www.coal.sierraclub.org/the-problem/dirty-truth-greenwashing-utilities](http://www.coal.sierraclub.org/the-problem/dirty-truth-greenwashing-utilities)

8. [www.martinot.info/organizations](http://www.martinot.info/organizations)

9. [www.sierraclub.org/](http://www.sierraclub.org/)

10. [www.profund.com](http://www.profund.com/)

11. [www.assets.bbhub.io/professional/sites/24/BNEF-EIRP-Climate-Scenarios-and-Energy-Investment-Ratios](http://www.assets.bbhub.io/professional/sites/24/BNEF-EIRP-Climate-Scenarios-and-Energy-Investment-Ratios)

12. [www.weforum.org/agenda/2023/02/low-carbon-investment-record-2022](http://www.weforum.org/agenda/2023/02/low-carbon-investment-record-2022)

13. [www.energy5.com/economic-benefits-of-renewable-energy](http://www.energy5.com/economic-benefits-of-renewable-energy)

14. [www.statistica.com/global-renewable-capacity-cumulative/2022](http://www.statistica.com/global-renewable-capacity-cumulative/2022)