technologies

Article

Geographical Dependence of Open Hardware Optimization: Case Study of Solar Photovoltaic Racking

Shafquat Rana [1], Nicholas Vandewetering [2], Jadyn Powell [1], Jonathan Álvarez Ariza [3] and Joshua M. Pearce [1,4,*]

[1] Department of Electrical & Computer Engineering, Western University, London, ON N6A 5B9, Canada; srana63@uwo.ca (S.R.); jpowel45@uwo.ca (J.P.)
[2] Department of Civil & Environmental Engineering, Western University, London, ON N6A 3K7, Canada; nvandew@uwo.ca
[3] Department of Technology in Electronics, Engineering Faculty, Corporación Universitaria Minuto de Dios-UNIMINUTO, Bogotá 111021, Colombia; jalvarez@uniminuto.edu
[4] Ivey Business School, Western University, London, ON N6G 0N1, Canada
* Correspondence: joshua.pearce@uwo.ca

Abstract: Open-source technological development is well-known for rapid innovation and providing opportunities to reduce costs and thus increase accessibility for a wide range of products. This is done through distributed manufacturing, in which products are produced close to end users. There is anecdotal evidence that these opportunities are heavily geographically dependent, with some locations unable to acquire components to build open hardware at accessible prices because of trade restrictions, tariffs, taxes, or market availability. Supply chain disruptions during the COVID-19 pandemic exacerbated this and forced designers to pivot towards a la carte-style design frameworks for critical system components. To further develop this phenomenon, a case study of free and open-source solar photovoltaic (PV) racking systems is provided. Two similar open-source designs made from different materials are compared in terms of capital costs for their detailed bill of materials throughout ten locations in North, Central and South America. The differences in economic optimization showed that the costs of wood-based racks were superior in North America and in some South American countries, while metal was less costly in Central and South America. The results make it clear that open hardware designs would be best to allow for local optimization based on material availability in all designs.

Keywords: open hardware; open source; open-source hardware; photovoltaic; solar energy; renewable energy; racking; design; open-source appropriate technology; appropriate technology

Citation: Rana, S.; Vandewetering, N.; Powell, J.; Ariza, J.Á.; Pearce, J.M. Geographical Dependence of Open Hardware Optimization: Case Study of Solar Photovoltaic Racking. *Technologies* **2023**, *11*, 62. https://doi.org/10.3390/technologies11020062

Academic Editor: Valeri Mladenov

Received: 14 March 2023
Revised: 16 April 2023
Accepted: 17 April 2023
Published: 21 April 2023

1. Introduction

The free and open-source licensing ignited rapid innovation [1,2] that now dominates the software industry [3,4]. Anyone can use, copy, study, and change the source code, which is openly shared to encourage others to voluntarily improve the design so that everyone benefits because they are required to share adaptations with the same license [5]. Hence, open-source technology development has become the ultimate gift economy [6], in terms of the software it has matured [7]. For instance, free/libre/open-source software (FOSS/FLOSS) has been integrated into 90% of cloud servers [8] (and all household-name internet companies) as well as 90% of Fortune 500 companies [9]. It is not surprising that all supercomputers use it [10]; additionally, >84% of smartphones also run it [11] and so does more than 80% of the Internet of Things (IOT) market [12].

The same accelerated innovation paradigm [13,14] has now taken hold with free and open-source hardware (FOSH) [15]. FOSH has the potential to democratize production [16,17] by manufacturing a wide range of physical products from toys [18,19] to high-tech scientific equipment [20,21] and medical hardware [22–24]. For example, in the electric vehicle (EV) sector, FOSH development has already started with open-source EV charging stations [25]. More notable, Tesla removed threats of intellectual property protectionism from their EV patents for those operating in good faith [26], as has Ford, to accelerate industry-wide EV development [27]. Open hardware has been created for different purposes, such as potentiostats/galvanostats to characterize thin film batteries [28], battery management [29], maintenance tools for EV batteries [30], the in situ monitoring of Li-ion cells [31], and even open-source all-iron batteries [32,33]. Following the same path as free and open-source software, open hardware has been shown to accelerate innovation [34–36], but lags behind software by approximately 15 years [37].

It is well-established in the literature that open technology development can create opportunities for distributed manufacturing that are able to radically reduce the price compared to commercial products manufactured using the traditional centralized paradigm [38–40]. These opportunities, however, are heavily geographically dependent. In poorer households, but particularly in developing countries or poor countries, individuals struggle with low incomes. Thus, not everyone can afford to purchase the necessary components to deploy open hardware. For technologies to be 'appropriate technologies' for the communities, they must consider their environmental, ethical, cultural, social, political, and economic aspects [41,42]. Technologies developed in such a way that are also licensed as open source are referred to as open-source appropriate technologies (OSAT) [43]. OSAT, particularly when coupled with distributed manufacturing, has the potential to drive sustainable development [44,45].

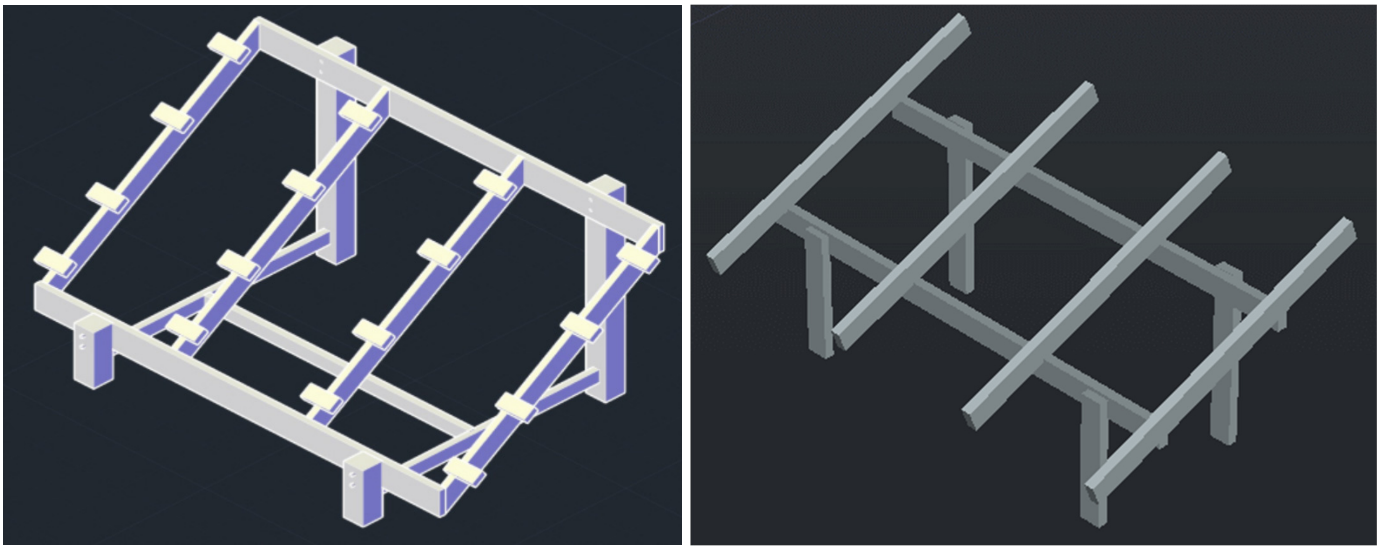
Even with high per capita incomes, some locations are unable to acquire components to build open hardware at accessible prices because of trade restrictions, tariffs, taxes, or market availability. This challenge of open hardware was brought into the spotlight with the supply chain disruptions observed during the COVID-19 pandemic [46,47], which forced open hardware designers to pivot towards a la carte-style design frameworks for critical components of a system [48]. This study probes this phenomenon using a case study of free and open-source solar photovoltaic (PV) racking systems. Solar PV system prices have declined rapidly in the last two decades [49–53], which has often made solar the lowest-cost option for electricity generation [54,55]. These low solar electricity prices have resulted in PV being the most rapidly expanding source of electricity [56], offering developing countries an enormous opportunity to leapfrog and directly electrify with renewable energy while meeting the U.N.'s 'Sustainable Energy for All' goals [57]. Similarly, in wealthy countries, middle-class consumers are also embracing distributed generation with PV to lower their electric utility bills [58,59]. In contrast, racking costs for PV systems have actually increased, so to help reduce costs and evaluate the geographic dependence of open hardware designs, two similar open hardware designs made from different materials are compared in terms of the capital costs for their detailed bill of materials throughout locations in North, Central and South America. An analysis of their economic differences in open hardware optimization is discussed in this context, and conclusions are drawn about the universal generalizability for open-hardware-based technologies. Technical considerations, limitations and future work derived from the previous analysis are then discussed.

The order of the manuscript is as follows. First, the case study of the solar photovoltaic racking is described. Next, the ten locations are provided for the market analysis. The results for the wood and metal material costs are provided in the results section. In the discussion of our materials selection, four considerations are evaluated: economics, fire resistance, electrical grounding, and physical attachment. Finally, conclusions are drawn.

2. Materials and Methods

2.1. Case Study Solar Photovoltaic Racking

Although installing PV is profitable in most of the world, it should be noted that temperature, solar flux, installed costs (materials and labor), and utility rate structure all play a role in that profitability and are geographically dependent. This study focuses primarily on the material cost of one subsystem (racking) or complete PV systems. Despite clear economic benefits, over the lifetime of a PV system (25 years under warranty), the capital cost is prohibitive for many consumers in both poor [60] and wealthy countries [61–64]. A method less-wealthy people can use to substantially reduce the up-front costs of PV systems (by 50% or more) is to adopt a do-it-yourself (DIY) approach [65]. Small DIY PV systems avoid most of the "soft costs", but still have USD/W costs that can be too expensive for some consumers. The historic PV system cost decreases are primarily because of reductions in PV module costs, while the racking and wiring relative costs have even become dominant on smaller systems [49,53]. Historically, PV racking (components that hold modules mechanically) was largely ignored by academics and industry, which focused on developing high-cost, overly complicated proprietary aluminum extrusion profiles for racking rails because the relative cost of the modules was so high. This resulted in only small cost decreases for PV racking [49]. Initial studies on open hardware approaches to PV racking are appropriate only for specialty applications with low tilt angles [66–68], but the majority of PV systems require a larger tilt angle. To fulfill this need, two open hardware PV racking systems have been designed from two materials: (a) wood [69] and (b) metal [70], as shown in Figure 1 (For full details on the step-by-step assembly and photographs of the complete PV systems, see these articles). Only two materials were selected, because for ground-mounted PV systems, they are the only two with widespread use and the majority are metal. Although there are some plastic racking materials for roof-mounted systems, in general, plastic racks are only used for low-tilt-angle systems. An economic analysis of the bill of materials (BOM) of the wood rack found savings of 49% to 77% compared to proprietary racking in Canada, but the savings were dependent on lumber costs, which vary widely throughout the world [69]. The partial BOMs of the racking systems focusing on the main structural components and costs are shown in Tables 1 and 2 for wood and metal, respectively. Both open-source racks are designed to hold three PV modules each of 400 W, so these racking systems are for 1.2 kW arrays. The systems can be replicated to meet the power needs of a specific application in these 1.2 kW modular arrays.



(**a**) (**b**)

Figure 1. Open hardware PV racking designs made from: (**a**) wood and (**b**) metal.

The major components seen in Figure 2 for the wood and metal racking system are nearly identical. The outside joists hold the side of portrait-oriented modules on the far right and far left of both racks. The inside joists do the same for the interior sides of the modules. Both designs have an equivalent number. Both systems have two beams. The wood system has them at the top and bottom of the racking, helping frame the modules. The metal members are parallel, running at about 1/3 and 2/3 of the module. The front and back posts are the upright members perpendicular to the ground that are secured into the ground with the same amount of concrete. They are different lengths in the two systems because of where they are attached to the racking system. The wood system needs lateral bracing, which is not present in the metal rack.

Table 1. Simplified BOM for the fixed-tilt wood-based PV racking system.

Component	Dimensions (m)	Quantity
Outside Joists	0.60 × 1.82 × 2.43	2
Inside Joists	0.60 × 2.43 × 2.43	2
Beams	0.60 × 2.43 × 3.04	2
Back Posts	1.82 × 1.82 × 2.43	2
Front Posts	1.21 × 1.21 × 3.04	1
Lateral Bracing	0.60 × 1.21 × 2.43	2
Lateral Bracing	0.60 × 1.21 × 3.04	1
Concrete	Bag (30 kg)	8

Table 2. BOM for the fixed-tilt aluminum-based PV racking system.

Component	Dimensions (m)	Quantity
Outside Joists	1.5 × 0.75 × 0.125	2
Inside Joists	2 × 1 × 0.125	2
Beams	1.5 × 0.75 × 0.125	2
Back Posts	2 × 1 × 0.995	2
Front Posts	1.5 × 0.75 × 0.125	2
Concrete	Bag (30 kg)	8

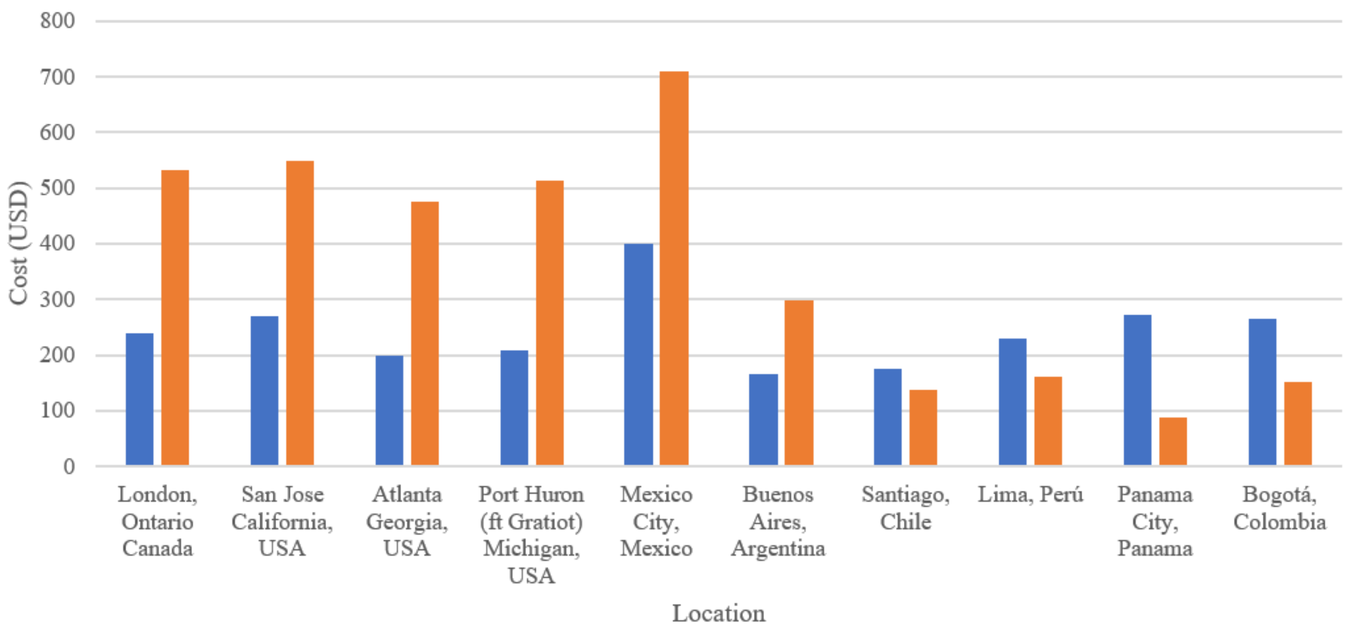


Figure 2. The capital costs of the BOM for the open hardware PV racks for both wood and aluminum are shown in ten cities/countries. Blue is the cost of the wood racks and orange is the cost of aluminum racks.

2.2. Market Analysis

Ten locations were selected throughout North, Central and South America:

- London, ON, Canada
- San Jose, CA, USA
- Atlanta, GA, USA
- Port Huron, MI, USA
- Mexico City, Mexico

- Buenos, Argentina
- Santiago, Chile
- Lima, Peru
- Panama City, Panama
- Bogotá, Colombia

The same methodology of sourcing the building materials for the open-source ground-mounted racks was implemented throughout the ten locations studied. Initially, pressure-treated wood and 6061-grade aluminum rectangular tubes of the provided dimensions were sourced. The availability of these grades of materials, however, varied by location, so when necessary, 6063-grade aluminum was substituted. When sourcing materials, large chain stores, such as Metal Supermarkets, The Home Depot, and Sodimac, were used as much as possible, given their large-scale distribution of stores. Full data for the analysis are available on the Open Science Framework [71]. When chain stores were not available, local providers of the area investigated were used. This methodology ensured that realistic values that actual distributed PV system builder would use in each country.

Finally, to help developers or user-developers make economic decisions about PV systems, the open-source Systems Advisory Model (SAM) (NREL, U.S.) was used to determine the PV system's electrical output. For each 1.2 kW system, the input parameters shown in Table 3 were used with the tilt angle being set by the latitude of the representative city selected for each country. The losses are considered using default values.

Table 3. Input parameters of SAM.

Parameters	**London, ON, Canada**	**San Jose, CA, USA**	**Atlanta, GA, USA**	**Port Huron, MI, USA**	**Mexico City, Mexico**	**Buenos, Argentina**	**Santiago, Chile**	**Lima, Peru**	**Panama City, Panama**	**Bogota, Colombia**
System Type	Residential									
PV Module	Heliene 72M–400 G1									
Module Type	Mono Crystalline Silicon									
Number of Modules	3									
Tilt Angle	43	34	35	43	19	45	35	12	9	4.6
Azimuth	180									
DC Power Rating	1.2 kWdc									
DC to AC Ratio	0.79									
Inverter	Altenergy Power System Inc: QS1A [240 V]									

3. Results

Sourcing the two BOMs in the ten countries (not only the correct grade of materials, but also the correct size) proved challenging. The standard sizes of the pressure-treated wood that was sold varied with metric versus imperial sizing in the various countries. This difference resulted in sourcing wood that was not exactly the provided dimensions. When necessary, larger-than-specified dimensions were chosen to ensure adequate materials to still meet Canadian building code standards [72], which accounted for both the heavy wind and snow loads used in the initial designs. The lengths of 6061 aluminum rectangular tubes available by region also varied. While the exact dimension was sourced when possible, some locations did not provide tubes of the correct length. Upon this occurrence, tubes of lengths longer than the given dimensions were selected to ensure adequate material to still meet mechanial requirements. Sourcing aluminum of the correct grade and dimensions was difficult in Mexico, so an American chain supplier was used, and an extra cost was added to account for shipping. The results for both the wood and aluminum BOM costs to build the PV racks are shown in Figure 2.

The prices of each material varied greatly by location, as well as which material would be more cost effective. In order to simulate a consumer as closely as possible, in each location the lowest price for each material/product from the BOM was evaluated by web market surveys for the location. Aluminum is the more expensive construction material in Canada, the U.S., Mexico and Argentina, whereas wood is more expensive in Chile, Peru, Panama and Colombia. The prices of the materials range widely, with the most expensive construction of the ground mount being with aluminum in Mexico, and the least expensive construction being with aluminum in Panama.

The difference in price between the two materials per location also varied (Figure 3). Canada, the U.S. and Mexico showed a very close price difference, being within a range of USD 33. The price difference of the remainder of the locations studied, however, varied by a much larger range. Chile had the lowest price difference between materials, of only USD 39, whereas Mexico had the largest price difference of USD 309.

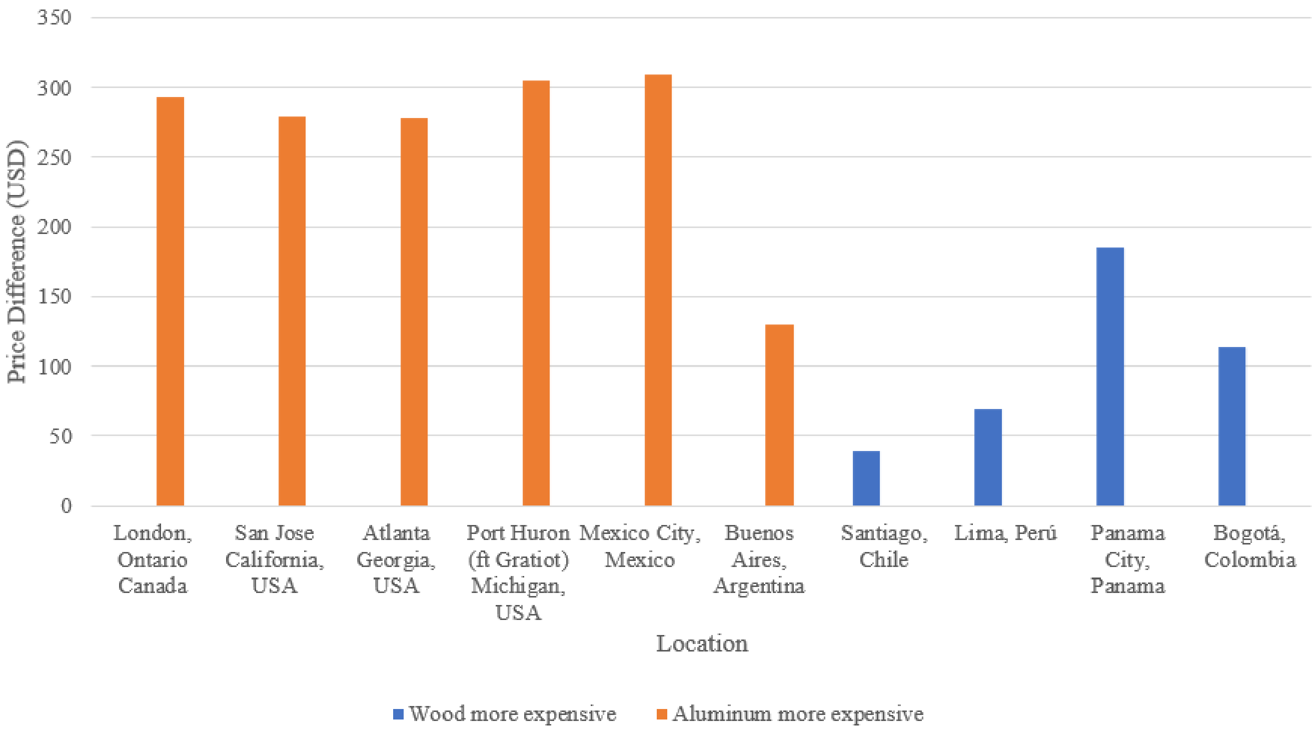


Figure 3. The difference in the capital costs of the open hardware PV based on materials selection in the ten cities/countries as well as the less expensive material denoted by color.

The prices of aluminum and wood for constructing the open-source PV racks do not follow a consistent pattern. The results are summarized geographically in Figure 4.

The electrical output simulated with SAM for the systems is summarized in Figure 5. As can be seen by Figure 5, the solar electric output varies by almost a factor of two between the lowest (Santiago, Chile) and highest (Mexico City, Mexico) solar flux locations. These values can be used as a first estimate for economic viability. The overall economics, however, will depend not only on the PV output but also many local specific factors. These factors will include personal information from users, such as financing costs and the value of electricity in each location, which is not only dependent on utility rate structures but also the type of user (e.g., residential or commercial) and what type of contract they are working under (e.g., net metering, power purchasing agreement, etc.). There is no performance difference between the two designs from the simulations, as there was not a physical factor included in the simulations that could have been used to differentiate them.

Figure 4. Results of economic analysis for wood and aluminum PV racking.

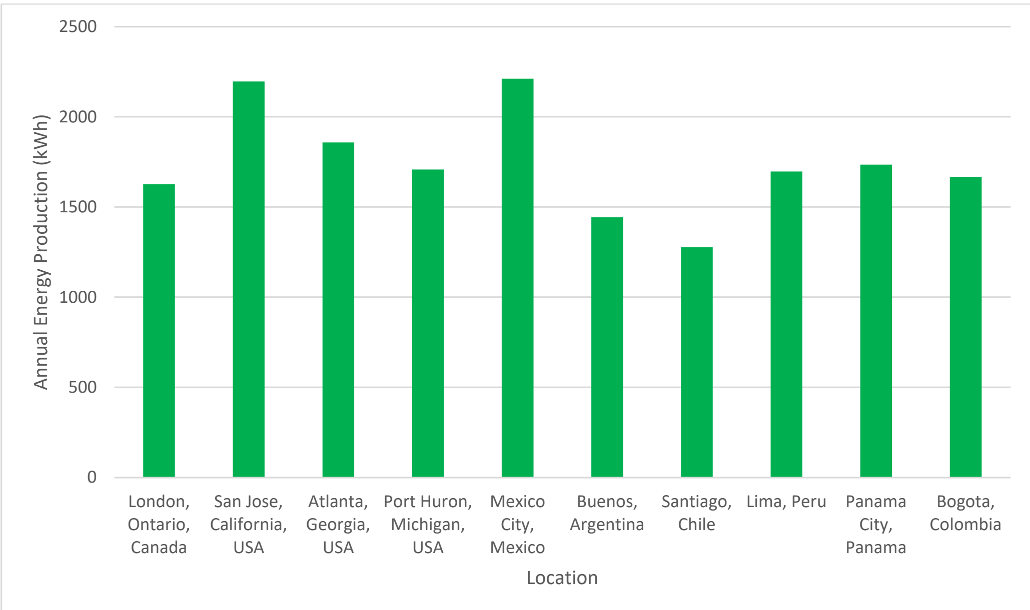


Figure 5. Annual PV electrical generation in kWh for the PV systems located in representative cities for each country evaluated.

4. Discussion and Future Work

4.1. Open Source PV Racking Material Selection Considerations

4.1.1. Economics

Both the open-source wood-based and metal-based racking systems are less expensive than their proprietary equals. As some communities are extremely sensitive to capital costs, depending on the region, one or the other material may be economically prohibitive and thus designs are made based on only one material may not necessarily be considered OSAT. Flexibility in the design and material selection makes a given design more likely to be OSAT and be deployed throughout the world. Building on a shared open-source design would allow small- and medium-sized companies throughout all of the Americas (and for that matter, the world) to form alliances to open hardware and leverage digital technologies [73] (e.g., CNC mills for manufacturing the components). Thus, they would be using the do-it-together (DIT) methodology [74] which is expected to accomplish more than by going about it alone [75]. There is still far more room for optimization (e.g., the designs were developed to meet Canadian building codes, which account for larger loads such as snow than those in some other regions). In addition, the members may also be able to be made smaller and thus less costly when optimizing for tilt angles closer to the equator. Similarly, the wood-rack used here has already evolved into a variable tilt model [76], which can collect about 5% more energy per year, and a vertical model [76], which is appropriate for field-based agrivoltaics. Thus, the DIT participatory design would lead to better products and collaborative production (e.g., global design, but national, state/province, local community manufacturing, or in the most extreme case, home-based manufacturing). DIT methodologies encourage local production from commons-based peer production [74,77–79], which generates positive externalities (rather than negative externalities, as for proprietary approaches to producing energy) for all the involved stakeholders (e.g., producers, prosumers, consumers and workers) [80]. DIT is perhaps best suited for small-scale local production that offers entrepreneurial opportunities and employment, as DIT provides a competitive advantage while also reducing the costs and risks of innovation [81].

In this particular case, the availability of low-cost building materials and types is the driving factor for the type of design employed. Although solar PV systems are economical, the racking system now is a substantive capital expense for them. Therefore, considering the example of the availability of low-cost solar racking materials in countries such as Canada, U.S, Argentina and Mexico can attract more producers and consumers towards a wood racking system, and DIY methodologies will provide them an alternative to choose and do it themselves, helping locals as well as others. Whereas in countries such as Chile, Peru, Panama, and Colombia, where aluminum is the less expensive option for solar racking, using them will make the solar PV system more economical. In countries where the difference between price of wood and aluminum is approximately the same, the driving factor is the type of material available rather than the cost itself. This highlights that the design material can change from one place to another depending on cost and availability, letting people in different countries use different materials to design the same system. The open-source wooden and metal racking techniques can help people to learn and implement ideas across the world. Proposals to build a detailed appropriate technology database by the U.N. or others would allow for a geographical information system to provide the optimal design for users based on local availability and the costs of materials [82]. This will be dependent on the specific local industries. For example, the aluminum industries in Chile [83], Peru [84], Panama [85] and Colombia [86] have a high export rate of aluminum, i.e., they are a good market for aluminum stakeholders. Similarly, Michigan, the U.S. [87] and Mexico [88] show robust lumber markets. These markets are consistent with the results of this study.

4.1.2. Fire Resistance and Weathering

Fire is not a threat to the aluminum racks, but it must be considered with wood-based racks. Thus, there is a need to consider the flammability and the quality of wood for making wood-based PV racks. Along with possessing strength, durability, and resistance to insects, decay and rot, the wood should be fire resistant. Commonly, pressure-treated pine, Douglas fir and cedar wood is used to make solar PV racks. Edison International [89] compared [90] timber's fire resistance and structural qualities against those of other materials that are more frequently employed in high-rise buildings. It demonstrated that wood is mechanically competitive with high-strength steel or concrete. The primary ecological benefit of wood, however, is its ability to absorb carbon dioxide, which, together with its high level of prefabrication, makes it a sustainable alternative that is gaining popularity and a good option for making wood racks in the future [90].

The lifetime of both racking systems is somewhat dependent on varying weather conditions in the different locations (e.g., snow loads in Canada or humidity factors in Central and South America). The lifetime of the aluminum racks is not a concern, as this is the PV industry standard and can match PV module warranties, which are generally around 25 years. Similarly, the pressure-treated lumber specified for the wood racking in this study would be expected to last for up to 40 years, which again is more than adequate to last for 25 years for the PV module warranty. In addition, pressure-treated lumber can be used in both humid and dry hot climates.

4.1.3. Electrical Grounding

The requirements and techniques used for the grounding of electrical equipment vary from one country to another, but there are some universal considerations for selecting a racking material. For example, PV systems with conventional metal-framed modules need to be grounded. The main goal of grounding various metal parts of electrical equipment is to reduce the damage caused to personnel and property by the fault current induced due to (i) insulation or mechanical failures; (ii) lightening; or (iii) surges or any adverse conditions that may energize the electrical components. When it comes to the grounding of electrical equipment, there are certain requirements, for example, set by the National Electrical Code (NEC) or National Fire Protection Association (NFPA 70), which must be followed in the U.S. [91] or the Canadian Electrical Code (CEC) in Canada [92].

The electrical equipment's grounding mechanism efficiently bonds (i.e., electrically connects) any exposed non-current-carrying metal elements together, eventually connecting these metal parts to the ground (see Figure 6). Similarly, according to NEC Section 690.43. for PV systems [91], when there are any exposed metals or conductive surfaces that could energize, equipment grounding systems are used to ground the system. This NEC requirement is applicable for any voltage of PV systems, even standalone 12-volt or 6-volt systems [93]. The electrically conductive elements with exposed metal surfaces are PV module frames, metal mounting racks, metal conduits, enclosures for combiners, disconnects, switchgears, inverters, and charge controllers, as well as other parts of a PV system that can cause fires and electrical shocks and need to be grounded. The grounding of the PV system, however, must match the grounding applied to the interconnected electrical system; if not, this may result in unexpected currents that follow into the PV system through the interface of connected power systems. Therefore, these faults conditions should be considered while designing the PV grounding system [93]. There are two methods used for the grounding of solar PV: (1) equipment grounding; or (2) system grounding. Equipment grounding is a traditional form in which all the non-current-carrying exposed metal parts are electrically connected and grounded. In system grounding, the negative wire of one of the two conductors coming out from the PV system is grounded. System grounding, however, increases the risk of fire if there is an excessive current flow, necessitating the addition of a fault fuse. Generally, in a metal racking system, the metal frames of the PV modules are physically in contact with the racking so only a single grounding connection is needed with a metal stake pounded into the ground.

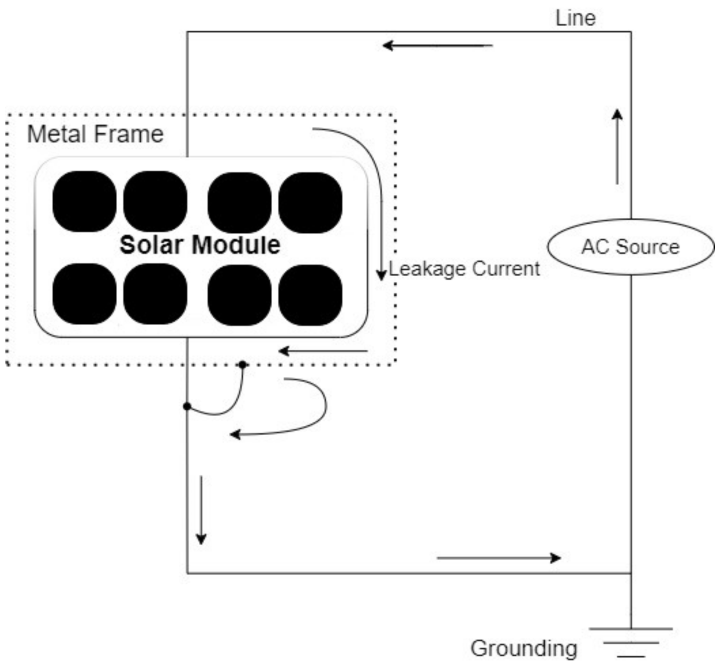


Figure 6. Conventional grounding of PV system with metal frame.

On the other hand, when a solar PV system is mounted on wooden racks, the metallic frameworks of the modules still need to be grounded. In most cases, the frames of the solar photovoltaic module are composed of anodized aluminum, which develops an anodized layer, or aluminum oxide, which is a rather effective insulator. Because of this, listed PV modules have a designated location where the equipment-grounding conductor can be connected. Typically, a stainless-steel screw is used to provide a strong electrical connection [94]. It should be noted that the aluminum frames are still exposed metal even though the anodized surface insulation on PV modules makes it difficult to achieve a reliable equipment grounding connection; however, it still needs to be grounded. Metallically bonding all the module frame's exposed metal surfaces together will require additional cables or wire, which will increase the cost of wiring for wood-based racking installations. Thus, the wood racks need an extra grounding cable for metal-framed PV modules.

Solar modules are typically double-isolated, i.e., solar modules have layers of encapsulant, tempered glass and a back sheet which protects it from moisture and dirt as well as keeps it electrically isolated. It is primarily the metal frames and racks that need grounding. A totally floating or double-insulated system (Type II insulation) has none of the current-carrying conductors grounded, and any exposed metal-conducting surfaces are effectively double-insulated from the current-carrying conductors, eliminating the need for the exposed conducting surfaces to be grounded [95].

In the case of frameless solar modules mounted on wood racks, since there is no exposed metal surface, it eliminates the need for grounding. Frameless modules require special clamping, which will be discussed in the next section. An alternative non-conducting frame option is the use of non-metallic frames. The South Korean company LG Chem has developed a new flame-retardant plastic material, named LUPOY EU5201, made by mixing acrylonitrite styrene acrylate with a polycarbonate base with glass fiber added to supplement its mechanical properties [96]. It can replace the aluminum frames of PV modules, making the frames much lighter and maintaining their mechanical properties with a low rate of thermal expansion and resistance to ultraviolet rays at a reasonable cost [96]. By replacing the metallic frame of a solar PV system with plastic and replacing the metallic racks with wooden racks, overall we can eliminate the need for grounding the solar PV modules entirely, thus offering the lowest-cost wiring if all other variables are constant. Future work is needed in this area. It should be noted, however, that other conductive metal parts need to be grounded.

4.1.4. Attachment

For speed of deployment, the mounting holes on the backs of PV modules are almost never employed on conventional ground mounts using metal racking. Proprietary clamps instead are bolted to the rack, and the clamps hold the modules in place by the frames [97]. The metal-based rack evaluated here (Figure 1b) can use the same method. The wood-based racks, however, used bolts through the back holes into wooden side pieces, as shown in Figure 7. This reduces the costs for the attachments, but also takes more time. This may be an opportunity to use the FOSH technique of replicating hardware from digital designs [98,99] so it can be customized [100] with free and open-source software [101]. Such a digital fabrication of open-source designs has been shown to allow for wealth growth [102] with a high return on investments [103,104]. This approach has been shown to provide the poor with a means to access high-value products, such as state-of-the-art equipment [105–108]. As an example, consider that scientific hardware costs are cut 87% when using open-source methods [104]. These savings can be increased when distributed with an open-source self-replicating rapid prototyper (RepRap) [109–112]. RepRaps have radically cut additive manufacturing costs already [113] and galvanized millions of free 3-D printing designs [114]. Such 3-D printers cut costs for mass-manufactured consumer goods by 90–99% [114,115] and could be applicable here for 3-D printing racking clamps. Future work is needed in this area.

Figure 7. Simple standard steel bolts can be used to attach a conventional PV module to a wood frame. The reflection of the bolt is seen in the PV cell in the bifacial module above it.

4.1.5. Advantages, Disadvantages and Future Work

The advantages of the open-source wood and metal PV racks are summarized in Table 4. The disadvantages of the wood-based rack include the following: needing to run an additional grounding wire for metal-frame-based panels, not being able to recycle treated wood, local PV installers not being familiar with it, and more susceptibility to sabotage (e.g., arson). The disadvantages of the metal are that it is less easy to work with than wood and may be more likely to be stolen in some areas than wood. Both systems currently have a disadvantage compared to established proprietary racks because of their novelty; they do not yet have vendors offering them as kits with warranties.

Table 4. Advantages of open-source wood-based and metal-based PV racking systems compared to conventional racking.

Advantages	Wood	Metal
Lower cost than proprietary racks	X	X
Uses local materials that are more easily sourced	X	X
Easier to find replacement components	X	X
Lower embodied energy of transportation	X	X
Supports local manufacturing jobs	X	X
No intellectual property costs or rents	X	X
Sustainable biobased material	X	
Recyclable		X
Able to be grounded normally		X

In addition to the future work outlined above, open-source racking based on these open-source racking designs can be extended to single-axis and dual-axis trackers [116–119]. There have already been some developments in low-concentration open-source racking using true ground mounts [120], which looks promising but needs a geographic analysis similar to the one in this article to determine if it is a realistic option globally. Far more work can be done to develop more conventional open-source concentration systems [121–124]. Finally, tracking racking, which is the most expensive option for high-concentration PV systems [125,126], may also offer the greatest opportunity for open-source racking redesign using common and readily accessible materials. It is thus a rich area for future work.

5. Conclusions

Solar PV systems are becoming clean and green alternative for electricity generation with economic benefits over their life cycle. The replacement of metal racking with wood racking has the potential to reduce costs in some regions, and this study showed that this is the case in North, Central and South America. Although a wood-based rack can save between 49% and 77% of the capital costs as compared to proprietary racking in Canada, the potential savings are extremely dependent on the location and cost of lumber. In this study, the aluminum and wood markets of ten countries in North, Central and South America are analyzed to determine the difference in the capital cost ranges of wood and its availability as well as to address one of the challenges of making solar photovoltaic racking economically accessible. The systems are designed to meet Canadian building code standards, which ensure the highest standards of mechanical safety but may add to the cost of system, as they were designed to handle snow loads that are not relevant in all of the countries analyzed. The use of proper grounding methods and both the lifetime and fire resistance of wood were provided to complement the solar PV system. For polymer frame or frameless PV modules, grounding is not necessary, but for conventional modules, an additional line of a conductor is needed to electrically link the frame of each model to a common ground. Overall, this study proves that the appropriateness of a given open hardware technology is extremely location-dependent; it varies based on the economics of different countries. The price difference between wood and metal is not linear and can vary non-linearly depending on the region. In this study, the price difference between wood and metal for solar PV racking systems starts decreasing in Mexico, Michigan, Canada, California, Atlanta, Panama, Colombia, Peru and Chile, respectively, with Mexico approximately having a price difference of a factor of 10 (USD 309 to USD 39) to that of Chile. It is clear that an open-source hardware-based wood-based solar PV racking system can complement DIY and DIT business models in many countries, but is not the most economical in some based on material availability and costs.

Author Contributions: Conceptualization, J.M.P.; Data curation, S.R., N.V., J.P. and J.Á.A.; Formal analysis, S.R., N.V. and J.P.; Funding acquisition, J.M.P.; Investigation, S.R., N.V., J.P., J.Á.A. and J.M.P.; Methodology, J.M.P.; Resources, J.M.P.; Supervision, J.M.P.; Validation, S.R. and J.P.; Visualization, S.R., N.V. and J.P.; Writing—original draft, S.R. and J.M.P.; Writing—review and editing, S.R., N.V., J.P., J.Á.A. and J.M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Thompson Endowment and the Natural Sciences and Engineering Research Council of Canada.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is available upon request.

Acknowledgments: This article benefited from helpful comments from Koami Soulemane Hayibo.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Raymond, E. The cathedral and the bazaar. *Knowl. Technol. Policy* **1999**, *12*, 23–49. [CrossRef]
2. Herstatt, C.; Ehls, D. *Open Source Innovation—The Phenomenon, Participant's Behavior, Business Implications*; Routledge: New York, NY, USA, 2015; ISBN 1-317-62425-4.
3. Lee, S.-Y.T.; Kim, H.-W.; Gupta, S. Measuring open source software success. *Omega* **2009**, *37*, 426–438. [CrossRef]
4. Weber, S. *The Success of Open Source*; Harvard University Press: Cambridge, MA, USA, 2005; ISBN 0-674-04499-1.
5. Lakhani, K.R.; Von Hippel, E. How Open Source Software Works: "Free" User-to-User Assistance. In *Produktentwicklung Mit Virtuellen Communities: Kundenwünsche Erfahren und Innovationen Realisieren*; Gabler Verlag: Wiesbaden, Germany, 2004; pp. 303–339.
6. Zeitlyn, D. Gift economies in the development of open source software: Anthropological reflections. *Res. Policy* **2003**, *32*, 1287–1291. [CrossRef]
7. Comino, S.; Manenti, F.M.; Parisi, M.L. From planning to mature: On the success of open source projects. *Res. Policy* **2007**, *36*, 1575–1586. [CrossRef]
8. Hiteshdawda. *Realising the Value of Cloud Computing with Linux*; Rackspace: San Antonio, TX, USA, 2020.
9. Parloff, R. *How Linux Conquered the Fortune 500*; Fortune: New York, NY, USA, 2013.
10. Supercomputers: All Linux, All the Time. Available online: https://www.zdnet.com/article/supercomputers-all-linux-all-the-time/ (accessed on 16 February 2023).
11. IDC. Smartphone Market Share. Available online: https://www.idc.com/promo/smartphone-market-share (accessed on 16 February 2023).
12. Eclipse IoT. IoT Developer Survey. 2019. Available online: https://iot.eclipse.org/community/resources/iot-surveys/assets/iot-developer-survey-2019.pdf (accessed on 13 March 2023).
13. Gal, M.S. Viral open source: Competition vs. synergy. *J. Compet. Law Econ.* **2012**, *8*, 469–506. [CrossRef]
14. Hausberg, J.P.; Spaeth, S. Why makers make what they make: Motivations to contribute to open source hardware development. *R D Manag.* **2020**, *50*, 75–95. [CrossRef]
15. Gibb, A. *Building Open Source Hardware: DIY Manufacturing for Hackers and Makers*; Pearson Education: London, UK, 2014; ISBN 0-321-90604-7.
16. Spaeth, S.; Hausberg, P. Can Open Source Hardware Disrupt Manufacturing Industries? The Role of Platforms and Trust in the Rise of 3d Printing. In *the Decentralized and Networked Future of Value Creation*; Springer: Cham, Switzerland, 2016; ISBN 3-319-31684-2.
17. Powell, A. Democratizing production through open source knowledge: From open software to open hardware. *Media Cult. Soc.* **2012**, *34*, 691–708. [CrossRef]
18. Petrovič, P.; Vaško, J. An Open Solution for a Low-Cost Educational Toy. In Proceedings of the Robotics in Education: Current Research and Innovations 10, Vienna, Austria, 10–12 April 2019; Springer: Cham, Switzerland, 2020; pp. 196–208.
19. Petersen, E.E.; Kidd, R.W.; Pearce, J.M. Impact of DIY Home Manufacturing with 3D Printing on the Toy and Game Market. *Technologies* **2017**, *5*, 45. [CrossRef]
20. Pearce, J.M. *Open-Source Lab: How to Build Your Own Hardware and Reduce Research Costs*; Newnes: New South Wales, Australia, 2013; ISBN 0-12-410486-X.
21. Oellermann, M.; Jolles, J.W.; Ortiz, D.; Seabra, R.; Wenzel, T.; Wilson, H.; Tanner, R.L. Open Hardware in Science: The Benefits of Open Electronics. *Integr. Comp. Biol.* **2022**, *62*, 1061–1075. [CrossRef]
22. Chagas, A.M.; Molloy, J.C.; Prieto-Godino, L.L.; Baden, T. Leveraging open hardware to alleviate the burden of COVID-19 on global health systems. *PLoS Biol.* **2020**, *18*, e3000730. [CrossRef]
23. Stirling, J.; Bowman, R. The COVID-19 Pandemic Highlights the Need for Open Design Not Just Open Hardware. *Des. J.* **2021**, *24*, 299–314. [CrossRef]

24. Pearce, J.M. Distributed Manufacturing of Open Source Medical Hardware for Pandemics. *J. Manuf. Mater. Process.* **2020**, *4*, 49. [CrossRef]
25. EVerest: The Open Source Software Stack for EV Charging Infrastructure. Available online: https://www.zdnet.com/article/everest-the-open-source-software-stack-for-electric-vehicle-charging-infrastructure/ (accessed on 16 February 2023).
26. All Our Patent Are Belong to You. Available online: https://www.tesla.com/blog/all-our-patent-are-belong-you (accessed on 16 February 2023).
27. The Green Living Guy. Ford Motor Company Announces Open Source Portfolio of EV Patents. Available online: https://greenlivingguy.com/2015/06/ford-motor-company-announces-open-source-portfolio-of-ev-patents/ (accessed on 16 February 2023).
28. Dobbelaere, T.; Vereecken, P.M.; Detavernier, C. A USB-controlled potentiostat/galvanostat for thin-film battery characterization. *Hardwarex* **2017**, *2*, 34–49. [CrossRef]
29. Sylvestrin, G.R.; Scherer, H.F.; Junior, O.H.A. Hardware and Software Development of an Open Source Battery Management System. *IEEE Lat. Am. Trans.* **2021**, *19*, 1153–1163. [CrossRef]
30. Carloni, A.; Baronti, F.; Di Rienzo, R.; Roncella, R.; Saletti, R. An Open-Hardware and Low-Cost Maintenance Tool for Light-Electric-Vehicle Batteries. *Energies* **2021**, *14*, 4962. [CrossRef]
31. Fleming, J.; Amietszajew, T.; McTurk, E.; Towers, D.P.; Greenwood, D.; Bhagat, R. Development and evaluation of in-situ instrumentation for cylindrical Li-ion cells using fibre optic sensors. *Hardwarex* **2018**, *3*, 100–109. [CrossRef]
32. Yensen, N.; Allen, P.B. Open source all-iron battery for renewable energy storage. *Hardwarex* **2019**, *6*, e00072. [CrossRef]
33. Koirala, D.; Yensen, N.; Allen, P.B. Open source all-iron battery 2.0. *Hardwarex* **2021**, *9*, e00171. [CrossRef]
34. Yip, M.C.; Forsslund, J. Spurring Innovation in Spatial Haptics: How Open-Source Hardware Can Turn Creativity Loose. *IEEE Robot. Autom. Mag.* **2017**, *24*, 65–76. [CrossRef]
35. Dosemagen, S.; Liboiron, M.; Molloy, J. Gathering for Open Science Hardware 2016. *J. Open Hardw.* **2017**, *1*, 4. [CrossRef]
36. Hsing, P.-Y. Sustainable Innovation for Open Hardware and Open Science–Lessons from The Hardware Hacker. *J. Open Hardw.* **2018**, *2*, 4. [CrossRef]
37. Pearce, J.M. Sponsored Libre Research Agreements to Create Free and Open Source Software and Hardware. *Inventions* **2018**, *3*, 44. [CrossRef]
38. Gibney, E. 'Open-hardware' pioneers push for low-cost lab kit. *Nature* **2016**, *531*, 147–148. [CrossRef] [PubMed]
39. Pearce, J.M. Cut costs with open-source hardware. *Nature* **2014**, *505*, 618. [CrossRef]
40. Arancio, J.; Tirado, M.M.; Pearce, J. Equitable Research Capacity Towards the Sustainable Development Goals: The Case for Open Science Hardware. *J. Sci. Policy Gov.* **2022**, *21*. [CrossRef]
41. Beder, S. The role of technology in sustainable development. *IEEE Technol. Soc. Mag.* **1994**, *13*, 14–19. [CrossRef]
42. Sianipar, C.P.M.; Yudoko, G.; Adhiutama, A.; Dowaki, K. Community Empowerment through Appropriate Technology: Sustaining the Sustainable Development. *Procedia Environ. Sci.* **2013**, *17*, 1007–1016. [CrossRef]
43. Pearce, J.M. The case for open source appropriate technology. *Environ. Dev. Sustain.* **2012**, *14*, 425–431. [CrossRef]
44. Gwamuri, J.; Pearce, J.M. Open source 3-D printers: An appropriate technology for building low cost optics labs for the developing communities. In Proceedings of the ETOP 2017, Hangzhou, China, 29–31 May 2017; Optica Publishing Group: Washington, DC, USA, 2017; p. 104522S. [CrossRef]
45. Pearce, J.M.; Blair, C.M.; Laciak, K.J.; Andrews, R.; Nosrat, A.; Zelenika-Zovko, I. 3-D Printing of Open Source Appropriate Technologies for Self-Directed Sustainable Development. *J. Sustain. Dev.* **2010**, *3*, p17. [CrossRef]
46. Critical Preparedness, Readiness and Response Actions for COVID-19. Available online: https://www.who.int/publications-detail-redirect/critical-preparedness-readiness-and-response-actions-for-covid-19 (accessed on 17 February 2023).
47. The Lancet. COVID-19: Too Little, Too Late? *Lancet* **2020**, *395*, 755. [CrossRef]
48. Oberloier, S.; Gallup, N.; Pearce, J. Overcoming supply disruptions during pandemics by utilizing found hardware for open source gentle ventilation. *Hardwarex* **2022**, *11*, e00255. [CrossRef] [PubMed]
49. Feldman, D.; Barbose, G.; Margolis, R.; Bolinger, M.; Chung, D.; Fu, R.; Seel, J.; Davidson, C.; Wiser, R. *Photovoltaic System Pricing Trends: Historical, Recent, and Near-Term Projections 2015 Edition*; National Renewable Energy Laboratory: Golden, CO, USA, 2016. [CrossRef]
50. Fu, R.; Feldman, D.J.; Margolis, R.M.U.S. *Solar Photovoltaic System Cost Benchmark: Q1 2018*; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2018.
51. Barron, A.R. Cost reduction in the solar industry. *Mater. Today* **2015**, *18*, 2–3. [CrossRef]
52. Tan, F. Solar Costs to Fall Further, Powering Global Demand—Irena. *Reuters*, 23 October 2017.
53. Matasci, S. Solar Panel Cost: Avg. Solar Panel Prices by State in 2019: EnergySage. Available online: https://www.energysage.com/local-data/solar-panel-cost/ (accessed on 13 April 2023).
54. Dudley, D. Renewable Energy Will Be Consistently Cheaper than Fossil Fuels by 2020, Report Claims. Available online: https://www.forbes.com/sites/dominicdudley/2018/01/13/renewable-energy-cost-effective-fossil-fuels-2020/ (accessed on 17 February 2023).
55. Solar Industry Research Data. Available online: https://www.seia.org/solar-industry-research-data (accessed on 17 February 2023).
56. Vaughan, A. Time to Shine: Solar Power Is Fastest-Growing Source of New Energy. *The Guardian*, 4 October 2017.

57. Levin, T.; Thomas, V.M. Can Developing Countries Leapfrog the Centralized Electrification Paradigm? *Energy Sustain. Dev.* **2016**, *31*, 97–107. [CrossRef]
58. Lang, T.; Ammann, D.; Girod, B. Profitability in absence of subsidies: A techno-economic analysis of rooftop photovoltaic self-consumption in residential and commercial buildings. *Renew. Energy* **2016**, *87*, 77–87. [CrossRef]
59. Prehoda, E.; Pearce, J.M.; Schelly, C. Policies to Overcome Barriers for Renewable Energy Distributed Generation: A Case Study of Utility Structure and Regulatory Regimes in Michigan. *Energies* **2019**, *12*, 674. [CrossRef]
60. Minigrids in the Money. Available online: https://rmi.org/insight/minigrids-money/ (accessed on 17 February 2023).
61. Alafita, T.; Pearce, J. Securitization of residential solar photovoltaic assets: Costs, risks and uncertainty. *Energy Policy* **2014**, *67*, 488–498. [CrossRef]
62. Rai, V.; Reeves, D.C.; Margolis, R. Overcoming barriers and uncertainties in the adoption of residential solar PV. *Renew. Energy* **2016**, *89*, 498–505. [CrossRef]
63. Horváth, D.; Szabó, R.Z. Evolution of photovoltaic business models: Overcoming the main barriers of distributed energy deployment. *Renew. Sustain. Energy Rev.* **2018**, *90*, 623–635. [CrossRef]
64. Yousaf, H.; Shakeel, S.R.; Rajala, A.; Raza, Z. Addressing Financial Barriers Influencing the Adoption of Solar PV: The Role of Business Models. In *Advances in Human Factors, Business Management and Leadership, Proceedings of the AHFE 2021 Virtual Conferences on Human Factors, Business Management and Society, and Human Factors in Management and Leadership, Online, 25–29 July 2021*; Springer: Cham, Switzerland, 2021; pp. 42–49.
65. Grafman, L.; Pearce, J.M. *To Catch the Sun*; Humboldt State University Press: Arcata, CA, USA, 2021.
66. Wittbrodt, B.; Laureto, J.; Tymrak, B.; Pearce, J.M. Distributed manufacturing with 3-D printing: A case study of recreational vehicle solar photovoltaic mounting systems. *J. Frugal Innov.* **2015**, *1*, 1. [CrossRef]
67. Wittbrodt, B.; Pearce, J.M. 3-D printing solar photovoltaic racking in developing world. *Energy Sustain. Dev.* **2017**, *36*, 1–5. [CrossRef]
68. Wittbrodt, B.; Pearce, J. Total U.S. cost evaluation of low-weight tension-based photovoltaic flat-roof mounted racking. *Sol. Energy* **2015**, *117*, 89–98. [CrossRef]
69. Vandewetering, N.; Hayibo, K.S.; Pearce, J.M. Impacts of Location on Designs and Economics of DIY Low-Cost Fixed-Tilt Open Source Wood Solar Photovoltaic Racking. *Designs* **2022**, *6*, 41. [CrossRef]
70. Vandewetering, N.; Hayibo, K.S.; Pearce, J.M. Open-Source Vertical Swinging Wood-Based Solar Photovoltaic Racking Systems. *Designs* **2023**, *7*, 34. [CrossRef]
71. Geographical Dependence of Open Hardware Optimization: Case Study of Solar Photovoltaic Racking. *Open Sci. Framew.* **2023**. [CrossRef]
72. National Research Council Canada. National Building Code of Canada 2015. Available online: https://nrc.canada.ca/en/certifications-evaluations-standards/codes-canada/codes-canada-publications/national-building-code-canada-2015 (accessed on 9 March 2023).
73. Fauchart, E.; Bacache-Beauvallet, M.; Bourreau, M.; Moreau, F. Do-It-Yourself or Do-It-Together: How digital technologies affect creating alone or with others? *Technovation* **2022**, *112*, 102412. [CrossRef]
74. Dupont, L.; Kasmi, F.; Pearce, J.M.; Ortt, R. Do-It-Together": Towards the Factories of the Future. In *Cosmo-Local Reader*; Ramos, J., Bauwens, M., Ede, S., Wong, J.G., Eds.; Futures Lab: London, UK, 2021; pp. 52–59.
75. Mahajan, S.; Luo, C.-H.; Wu, D.-Y.; Chen, L.-J. From Do-It-Yourself (DIY) to Do-It-Together (DIT): Reflections on designing a citizen-driven air quality monitoring framework in Taiwan. *Sustain. Cities Soc.* **2020**, *66*, 102628. [CrossRef]
76. Vandewetering, N.; Hayibo, K.S.; Pearce, J.M. Open-Source Design and Economics of Manual Variable-Tilt Angle DIY Wood-Based Solar Photovoltaic Racking System. *Designs* **2022**, *6*, 54. [CrossRef]
77. Dupont, L.; Kasmi, F.; Pearce, J.M.; Ortt, R.J. "Do-It-Together" and Innovation: Transforming European Industry. *J. Innov. Econ. Manag.* **2023**, *40*, 1–11. [CrossRef]
78. Benkler, Y.; Nissenbaum, H. Commons-based Peer Production and Virtue. *J. Political Philos.* **2006**, *14*, 394–419. [CrossRef]
79. Bauwens, M.; Pantazis, A. The ecosystem of commons-based peer production and its transformative dynamics. *Sociol. Rev.* **2018**, *66*, 302–319. [CrossRef]
80. Hirscher, A.-L.; Niinimäki, K.; Armstrong, C.M.J. Social manufacturing in the fashion sector: New value creation through alternative design strategies? *J. Clean. Prod.* **2018**, *172*, 4544–4554. [CrossRef]
81. Cullmann, S.; Guittard, C.; Schenk, E. Participative creativity serving product design in SMEs: A case study. *J. Innov. Econ. Manag.* **2015**, *18*, 79–98. [CrossRef]
82. UN Centralised Database of Open-Source Appropriate Technologies; United Nations Conference on Trade and Development, 2021. Contribution to ECOSOC Resolution E/RES/2021/30. Available online: https://unctad.org/publication/note-proposed-united-nations-centralised-database-open-source-appropriate-technologies (accessed on 13 March 2023).
83. Chile Aluminum: Exports, 1995–2023 | CEIC Data. Available online: https://www.ceicdata.com/en/indicator/chile/aluminum-exports (accessed on 19 February 2023).
84. Peru Aluminium Industry Outlook 2022–2026. Available online: https://www.reportlinker.com/clp/country/15854/726274 (accessed on 19 February 2023).
85. Panama Aluminium Industry Outlook 2022–2026. Available online: https://www.reportlinker.com/clp/country/15854/726313 (accessed on 19 February 2023).

86. Colombia Exports of Aluminum–2023 Data 2024 Forecast 1991–2021 Historical. Available online: https://tradingeconomics.com/colombia/exports/aluminum (accessed on 19 February 2023).
87. Michigan's Forest Products Industry's Value Spikes–Michigan Farm News. Available online: https://www.michiganfarmnews.com/privacy-and-security (accessed on 19 February 2023).
88. Arias, E. *Mexico: Market Profile*; South Carolina Forestry Commission: Columbia, SC, USA, 2019.
89. Wainwright, O. 'I Want to Caress the Lift!': The Eco Office Block Miracle Made Entirely from Wood. *The Guardian*, 30 January 2023.
90. Orta, B.; Martínez-Gayá, J.E.; Cervera, J.; Aira, J.R. Timber High Rise, State of the Art. *Inf. Construcción* **2020**, *72*, e346. [CrossRef]
91. NFPA 70®: National Electrical Code®. Available online: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=70 (accessed on 15 February 2023).
92. Canadian Electrical Code Products. Available online: https://www.csagroup.org/store/canadian-electrical-code-products/ (accessed on 15 February 2023).
93. Wiles, J.C., Jr. *Solar America Board for Codes and Standards Photovoltaic System Grounding*; Solar America Board for Codes and Standards: Orlando, FL, USA, 2012.
94. Wiles, J. To Ground or Not to Ground: That Is Not the Question (in the USA). *Home Power* **1999**, *72*, 112–117.
95. Bower, W.I.; Wiles, J.C. Analysis of Grounded and Ungrounded Photovoltaic Systems. In Proceedings of the 1994 IEEE 1st World Conference on Photovoltaic Energy Conversion–WCPEC (A Joint Conference of PVSC, PVSEC and PSEC), Waikoloa, HI, USA, 5–9 December 1994; Volume 1, pp. 809–812.
96. Hutchins, M. A Lightweight Plastic to Replace Aluminum Module Frames. Available online: https://www.pv-magazine.com/2021/10/19/lightweight-plastic-material-to-replace-aluminum-frames/ (accessed on 7 February 2023).
97. IRWIN QUICK-GRIP Clamps, One-Handed, Mini Bar, 6-Inch, 4-Pack (1964758): Amazon.ca: Tools & Home Improvement. Available online: https://www.amazon.ca/IRWIN-QUICK-GRIP-One-Handed-Mini-Clamp/dp/B001DSY4QO/ (accessed on 21 February 2023).
98. Fernando, P. Tools for Public Participation in Science: Design and Dissemination of Open-Science Hardware. In Proceedings of the 2019 on Creativity and Cognition, San Diego CA USA, 23–26 June 2019; pp. 697–701.
99. Pearce, J.M. Quantifying the Value of Open Source Hard-ware Development. *Mod. Econ.* **2015**, *6*, 1–11. [CrossRef]
100. Daniel, K.F.; Peter, J.G. Open-source hardware is a low-cost alternative for scientific instrumentation and research. *Mod. Instrum.* **2012**, *1*, 8–20. [CrossRef]
101. Oberloier, S.; Pearce, J.M. Open source low-cost power monitoring system. *Hardwarex* **2018**, *4*, e00044. [CrossRef]
102. Thompson, C. Build It. Share It. Profit. Can Open Source Hardware Work. *Wired Magazine*, 20 October 2011.
103. Pearce, J. Return on investment for open source scientific hardware development. *Sci. Public Policy* **2016**, *43*, 192–195. [CrossRef]
104. Pearce, J.M. Economic savings for scientific free and open source technology: A review. *Hardwarex* **2020**, *8*, e00139. [CrossRef]
105. Harnett, C. Open source hardware for instrumentation and measurement. *IEEE Instrum. Meas. Mag.* **2011**, *14*, 34–38. [CrossRef]
106. Pearce, J.M. Building Research Equipment with Free, Open-Source Hardware. *Science* **2012**, *337*, 1303–1304. [CrossRef] [PubMed]
107. Chagas, A.M. Haves and have nots must find a better way: The case for open scientific hardware. *PLoS Biol.* **2018**, *16*, e3000014. [CrossRef] [PubMed]
108. Wenzel, T. Open hardware: From DIY trend to global transformation in access to laboratory equipment. *PLoS Biol.* **2023**, *21*, e3001931. [CrossRef] [PubMed]
109. Sells, E.; Bailard, S.; Smith, Z.; Bowyer, A.; Olliver, V. RepRap: The Replicating Rapid Prototyper: Maximizing Customizability by Breeding the Means of Production. In *Handbook of Research in Mass Customization and Personalization: (In 2 Volumes)*; World Scientific: Singapore, 2010; pp. 568–580.
110. Jones, R.; Haufe, P.; Sells, E.; Iravani, P.; Olliver, V.; Palmer, C.; Bowyer, A. RepRap—The replicating rapid prototyper. *Robotica* **2011**, *29*, 177–191. [CrossRef]
111. Kentzer, J.; Koch, B.; Thiim, M.; Jones, R.W.; Villumsen, E. An open source hardware-based mechatronics project: The replicating rapid 3-D printer. In Proceedings of the 2011 4th International Conference on Mechatronics (ICOM), Kuala Lumpur, Malaysia, 17–19 May 2011; pp. 1–8. [CrossRef]
112. Bowyer, A. 3D Printing and Humanity's First Imperfect Replicator. *3D Print. Addit. Manuf.* **2014**, *1*, 4–5. [CrossRef]
113. Rundle, G. *A Revolution in the Making*; Affirm Press: South Melbourne, Australia, 2014; ISBN 1-922213-48-9.
114. Wittbrodt, B.T.; Glover, A.G.; Laureto, J.; Anzalone, G.C.; Oppliger, D.; Irwin, J.L.; Pearce, J.M. Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers. *Mechatronics* **2013**, *23*, 713–726. [CrossRef]
115. Petersen, E.E.; Pearce, J. Emergence of Home Manufacturing in the Developed World: Return on Investment for Open-Source 3-D Printers. *Technologies* **2017**, *5*, 7. [CrossRef]
116. Hafez, A.Z.; Yousef, A.M.; Harag, N.M. Solar tracking systems: Technologies and trackers drive types–A review. *Renew. Sustain. Energy Rev.* **2018**, *91*, 754–782. [CrossRef]
117. Awasthi, A.; Shukla, A.K.; Murali Manohar, S.R.; Dondariya, C.; Shukla, K.N.; Porwal, D.; Richhariya, G. Review on sun tracking technology in solar PV system. *Energy Rep.* **2020**, *6*, 392–405. [CrossRef]
118. Mpodi, E.K.; Tjiparuro, Z.; Matsebe, O. Review of Dual Axis Solar Tracking and Development of Its Functional Model. *Procedia Manufacturing* **2019**, *35*, 580–588. [CrossRef]
119. Seme, S.; Štumberger, B.; Hadžiselimović, M.; Sredenšek, K. Solar Photovoltaic Tracking Systems for Electricity Generation: A Review. *Energies* **2020**, *13*, 4224. [CrossRef]

120. Hollman, M.R.; Pearce, J.M. Geographic potential of shotcrete photovoltaic racking: Direct and low-concentration cases. *Sol. Energy* **2021**, *216*, 386–395. [CrossRef]
121. Amanlou, Y.; Hashjin, T.T.; Ghobadian, B.; Najafi, G.; Mamat, R. A comprehensive review of Uniform Solar Illumination at Low Concentration Photovoltaic (LCPV) Systems. *Renew. Sustain. Energy Rev.* **2016**, *60*, 1430–1441. [CrossRef]
122. Andrews, R.W.; Pollard, A.; Pearce, J.M. Photovoltaic system performance enhancement with non-tracking planar concentrators: Experimental results and BDRF based modelling. In Proceedings of the 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC), Tampa, FL, USA, 16–21 June 2013; pp. 229–234. [CrossRef]
123. Yadav, P.; Tripathi, B.; Rathod, S.; Kumar, M. Real-time analysis of low-concentration photovoltaic systems: A review towards development of sustainable energy technology. *Renew. Sustain. Energy Rev.* **2013**, *28*, 812–823. [CrossRef]
124. Dellicompagni, P.R.; Heim, D.; Knera, D.; Krempski-Smejda, M. A Combined Thermal and Electrical Performance Evaluation of Low Concentration Photovoltaic Systems. *Energy* **2022**, *254*, 124247. [CrossRef]
125. Rodrigo, P.; Fernández, E.; Almonacid, F.; Pérez-Higueras, P. Models for the electrical characterization of high concentration photovoltaic cells and modules: A review. *Renew. Sustain. Energy Rev.* **2013**, *26*, 752–760. [CrossRef]
126. Gómez-Gil, F.J.; Wang, X.; Barnett, A. Energy production of photovoltaic systems: Fixed, tracking, and concentrating. *Renew. Sustain. Energy Rev.* **2012**, *16*, 306–313. [CrossRef]