Hidrogênio verde, armazenamento de energia, mobilidade elétrica e energia solar fotovoltaica

Prof. Ricardo Rüther
Universidade Federal de Santa Catarina
Laboratório Fotovoltaica/UFSC

www.fotovoltaica.ufsc.br

UNIVERSIDADE FEDERAL DE SANTA CATARINA

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Photovoltaics: new technology?

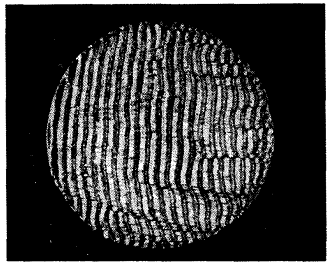

FIG. 1. End view of 0.50 caliber cylindrical steel projectile after it has passed through a 0.005-in. lead target at 45 deg striking angle. The actual diameter of this cylinder is 0.428 in.

Figure 1 is a photograph of the end of a 0.50 caliber cylindrical steel projectile after it has penetrated a 0.005-in. lead target aligned at a 45 deg striking angle. Figure 2 is a photomicrograph of a cross section of a cylinder that shows the wave structure of the ridges. Although the mechanism responsible for production of these waves is somewhat obscure, the critical angle 2φ is believed to be the same critical angle discussed by the Los Alamos group[1] in a paper that deals with metal plates accelerated together by high explosive charges. The Los Alamos group has discussed the asymmetric collision of dissimilar solids, but has not yet reported any experimental data. The specimens shown in Figs. 1 and 2 correspond to the asymmetric case.

The experiment was modified to obtain symmetric collision. Steel projectiles with conical noses specified by the half-angle $\pi/2-\theta$ were fired into steel targets aligned at the striking angle θ. Plastic deformation occurs along one of the elements of the cone provided that $2\theta > 2\varphi$. Negligible plastic deformation occurs if $2\theta < 2\varphi$. The critical angle 2φ determined by this experiment is in excellent agreement with the predicted[1] value for iron. Two preliminary determinations indicate the value $2\varphi = 7.7$ deg for a projectile velocity of 0.87 mm/μsec. This velocity corresponds to the plate velocity $v_p = 0.43$ mm/μsec of Fig. 15 in reference 1.

The experiment discussed is believed to be equivalent to that of the Los Alamos group. No theoretical or experimental difficulty is expected if the technique is extended to higher velocities and to solids other than steel. The experiment is expected to be of value in checking and determining equation of state data of solids in the megabar pressure regime. As a basis for comparison, the compressibility of pure iron has been measured up to a maximum pressure of only 0.03 megabar.[2] The pressure produced at the critical angle 2φ by the symmetric collision of steel is 0.47 megabar, a value calculated from the published[1] equation of state of iron.

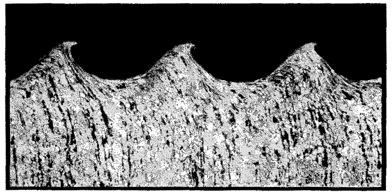

FIG. 2. Photomicrograph of a cross section of a projectile which shows the wave structure formed by 45 deg impact on a 0.010-in. lead target. The average distance from crest to crest is 0.033 in.

[1] Walsh, Shreffler, and Willig, J. Appl. Phys. 24, 349 (1953).
[2] P. W. Bridgman, Revs. Modern Phys. 18, 1 (1946).

A New Silicon *p-n* Junction Photocell for Converting Solar Radiation into Electrical Power

D. M. CHAPIN, C. S. FULLER, AND G. L. PEARSON
Bell Telephone Laboratories, Inc., Murray Hill, New Jersey

(Received January 11, 1954)

THE direct conversion of solar radiation into electrical power by means of a photocell appears more promising as a result of recent work on silicon *p-n* junctions. Because the radiant energy is used without first being converted to heat, the theoretical efficiency is high.

Photons of 1.02 electron volts ($\lambda = 1.2$ microns) are able to produce electron-hole pairs in silicon. In the presence of a *p-n* barrier, these electron-hole pairs are separated and made to do work in an external circuit. All of the light of wavelength shorter than 1.2 microns is potentially useful for generating electron-hole pairs but the efficiency of energy conversion decreases for short wavelengths because the energy above the necessary 1.02 electron volts is wasted. Allowing for this loss and assuming a working voltage of 0.5 volt, which is near the maximum measured, a computation over the entire solar spectrum indicates a limiting efficiency of approximately 22 percent for a cell of negligible internal losses and for utilization of all possible electron-hole pairs.

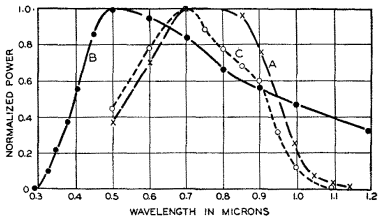

FIG. 1. Normalized spectral energy distribution. (A) Silicon photocell equi-energy response. (B) Solar energy at earth's surface. (C) Curve *A* times Curve *B*.

Several practical factors lower this figure. The untreated silicon surface reflects about half of the incident radiation. Some of this can be saved by proper surface treatment. The second serious loss is recombination of electron-hole pairs before they reach the *p-n* barrier. Penetration of radiation over most of the useful spectrum is extremely shallow so that it becomes necessary to place the *p-n* junction as near to the surface as possible except for the third serious loss. This is the I^2R loss caused by resistance in the surface layer and by contact resistance. Extremely small cells minimize the resistance loss and give useful data. For cells of several square centimeters, special geometry of contacts will minimize resistance losses.

Present work on silicon *p-n* photocells uses a thin layer of *p*-type silicon formed over an *n*-type base. The surface layer is less than 0.0001 inch thick. Figure 1 shows the spectral response for one such cell. Curve *A* is the measured power output for equal intensities of weak radiation as a function of wavelength. Maxi-

The first Si PV solar cell has already turned 69 years old!

The first solar PV cell was 6% efficient in 1954

Solar cells are made of Si
Si is the second most abundant element on Earth (> 25% of Earth's surface)

1954: First Solar Cell
2000: First 1 GWp of cumulative production
2023: 300 GWp annual production
> 1200 GWp of cumulative production

Solar is about the same age as nuclear:
The Atomic Energy Commission authorized the construction of Experimental Breeder Reactor I at a site in Idaho. The reactor generated the first electricity from nuclear energy on December 20, 1951. Enrico Fermi led a group of scientists in initiating the first self-sustaining nuclear chain reaction.

https://www.youtube.com/watch?v=QJKzq0EcC5w

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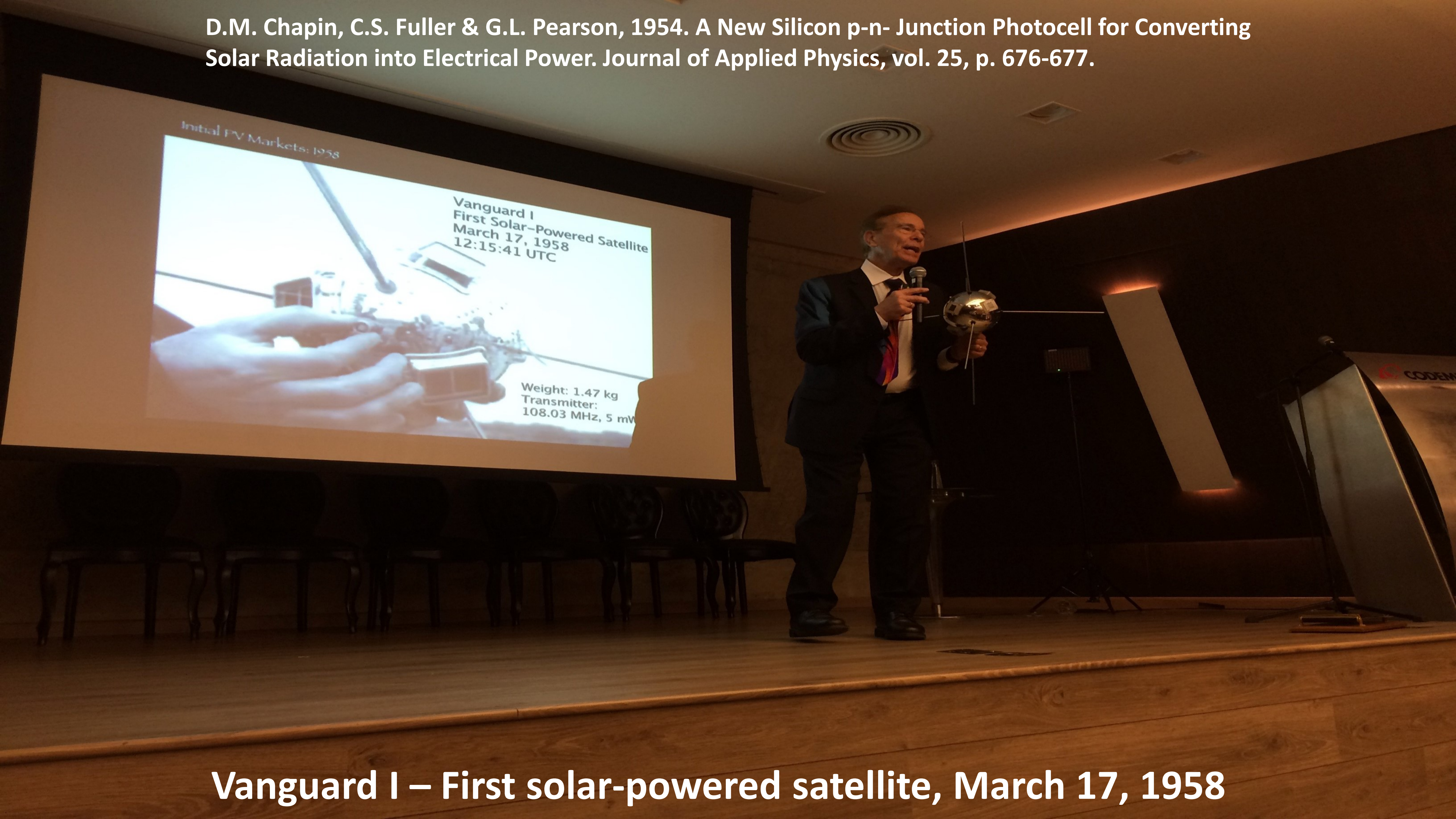
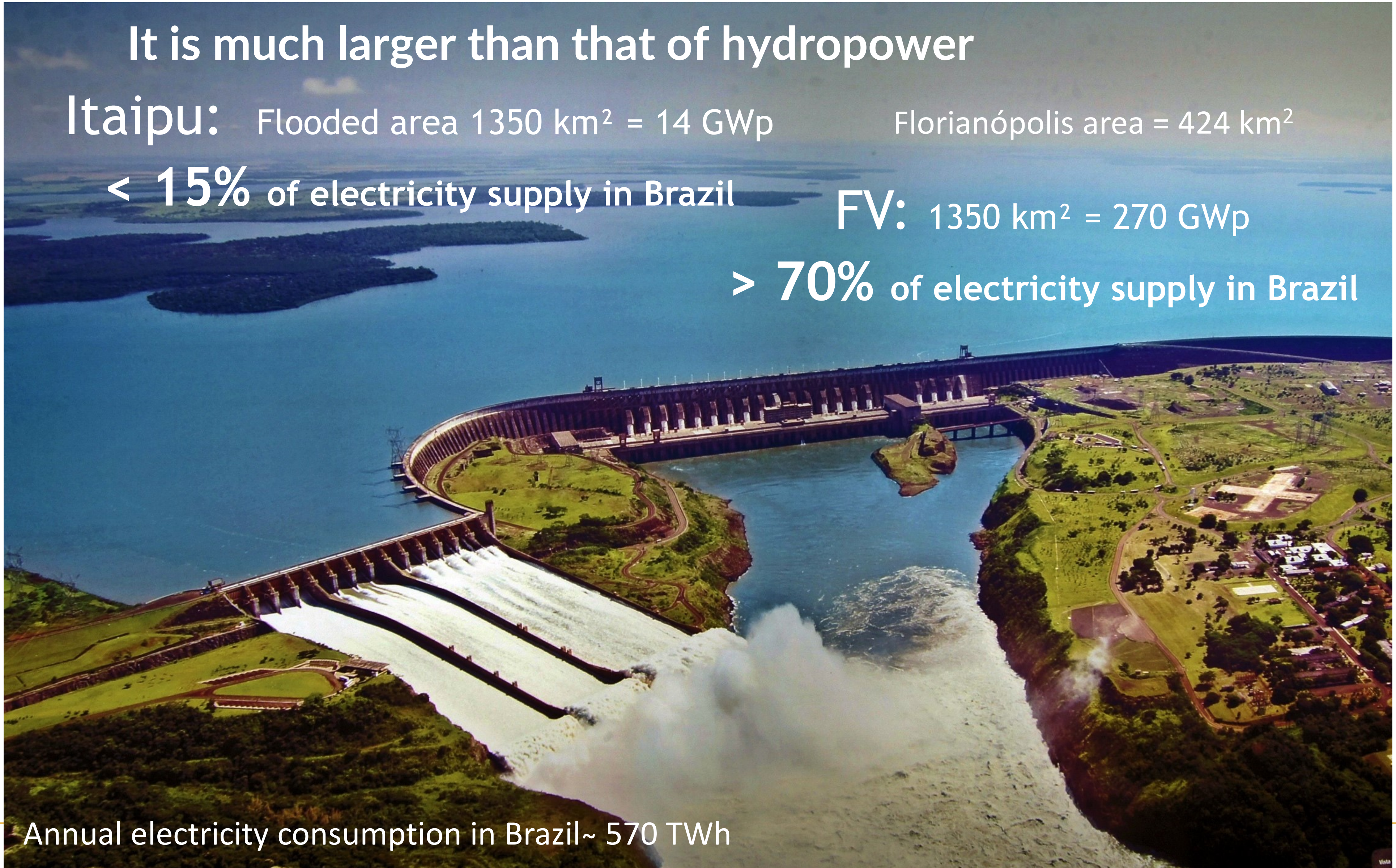
D.M. Chapin, C.S. Fuller & G.L. Pearson, 1954. A New Silicon p-n- Junction Photocell for Converting Solar Radiation into Electrical Power. Journal of Applied Physics, vol. 25, p. 676-677.



Vanguard I – First solar-powered satellite, March 17, 1958

How reliable is this technology?

What is the PV potential?



Floating PV

Hydropower installed capacity in Brazil: ~ 110 GW
Flooded area of all hydropower plants in Brazil combined: 40.000 km^2
How much PV can we fit in this area: **8.000 GWp (8 TWp)** !!! (World 1.3 TWp)

PHOTOVOLTAICS EVERYWHERE

A hybrid wind and solar power station near Zhangjiakou in Hebei province, northwestern China. Credit: Chen Xiaodong/VCG via Getty

PHOTOVOLTAICS EVERYWHERE

Nature vol 603, 24Mar2022, Spotlight: China’s net-zero ambitions,

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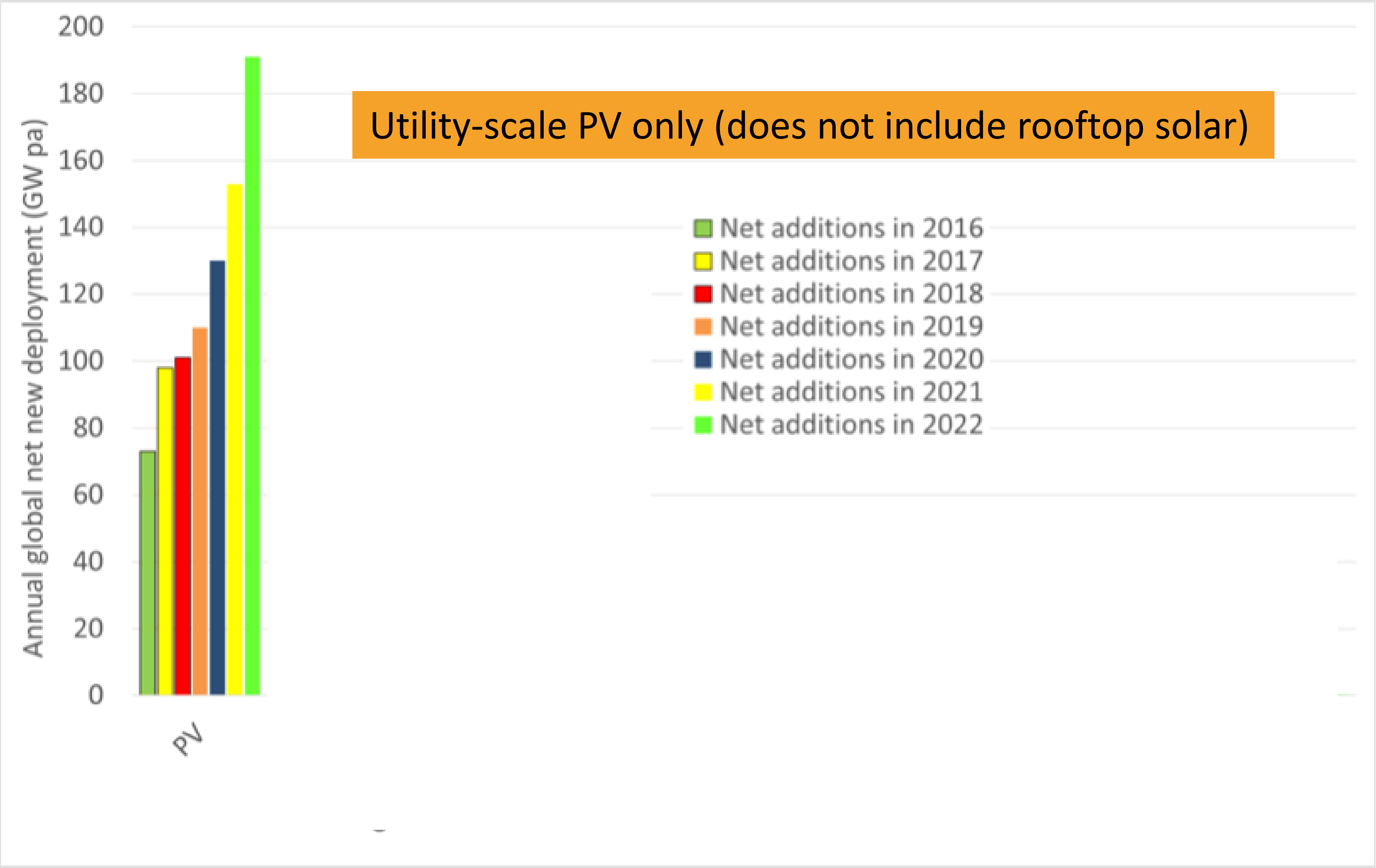
PHOTOVOLTAICS EVERYWHERE

Agri PV

Simultaneous use of the land for agriculture and solar PV generation

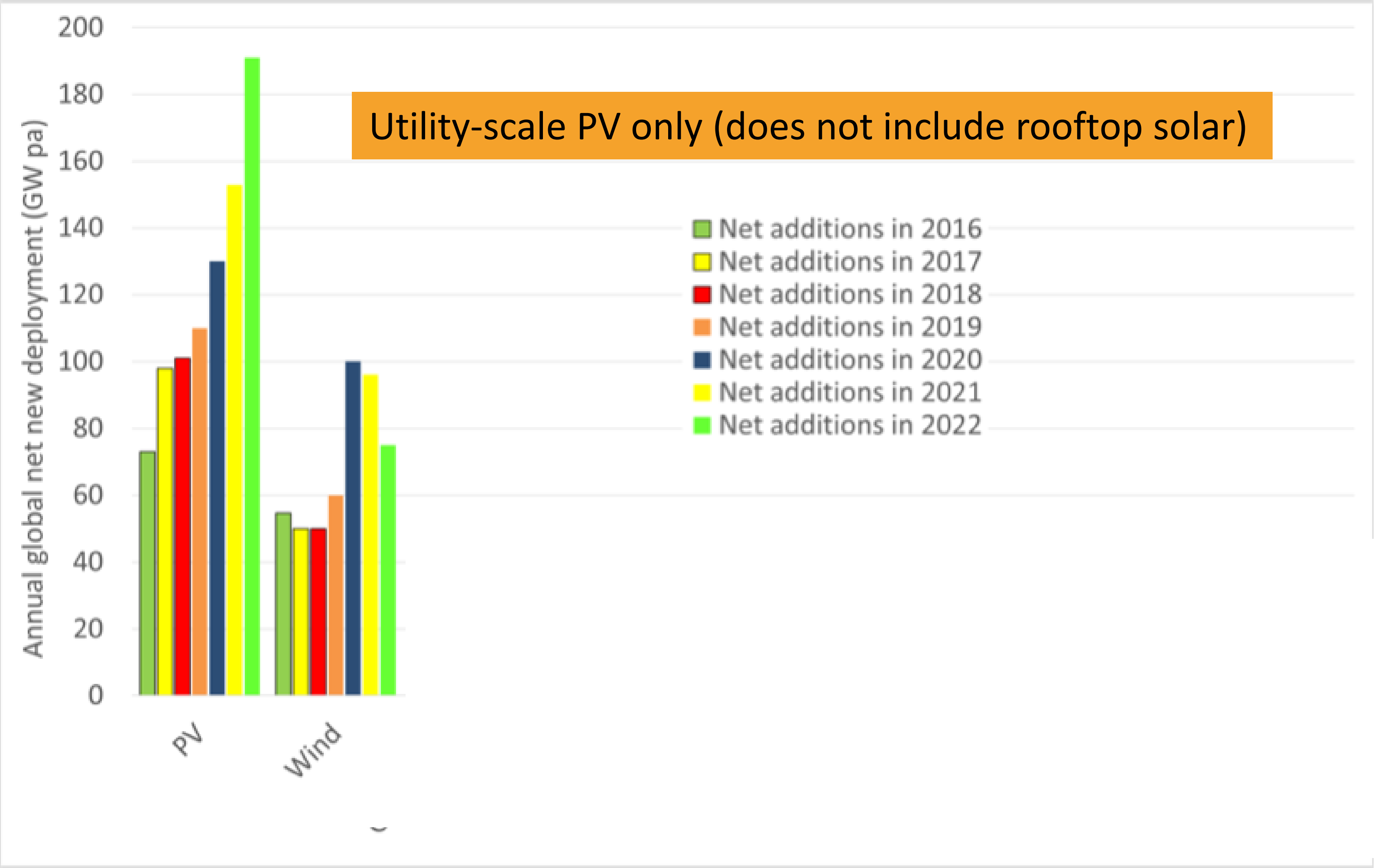
Fraunhofer ISE

SOLAR PV IS THE FASTEST ENERGY GENERATION TECHNOLOGY WORLDWIDE



https://ieeexplore.ieee.org/document/8836526

SOLAR PV IS THE FASTEST ENERGY GENERATION TECHNOLOGY WORLDWIDE



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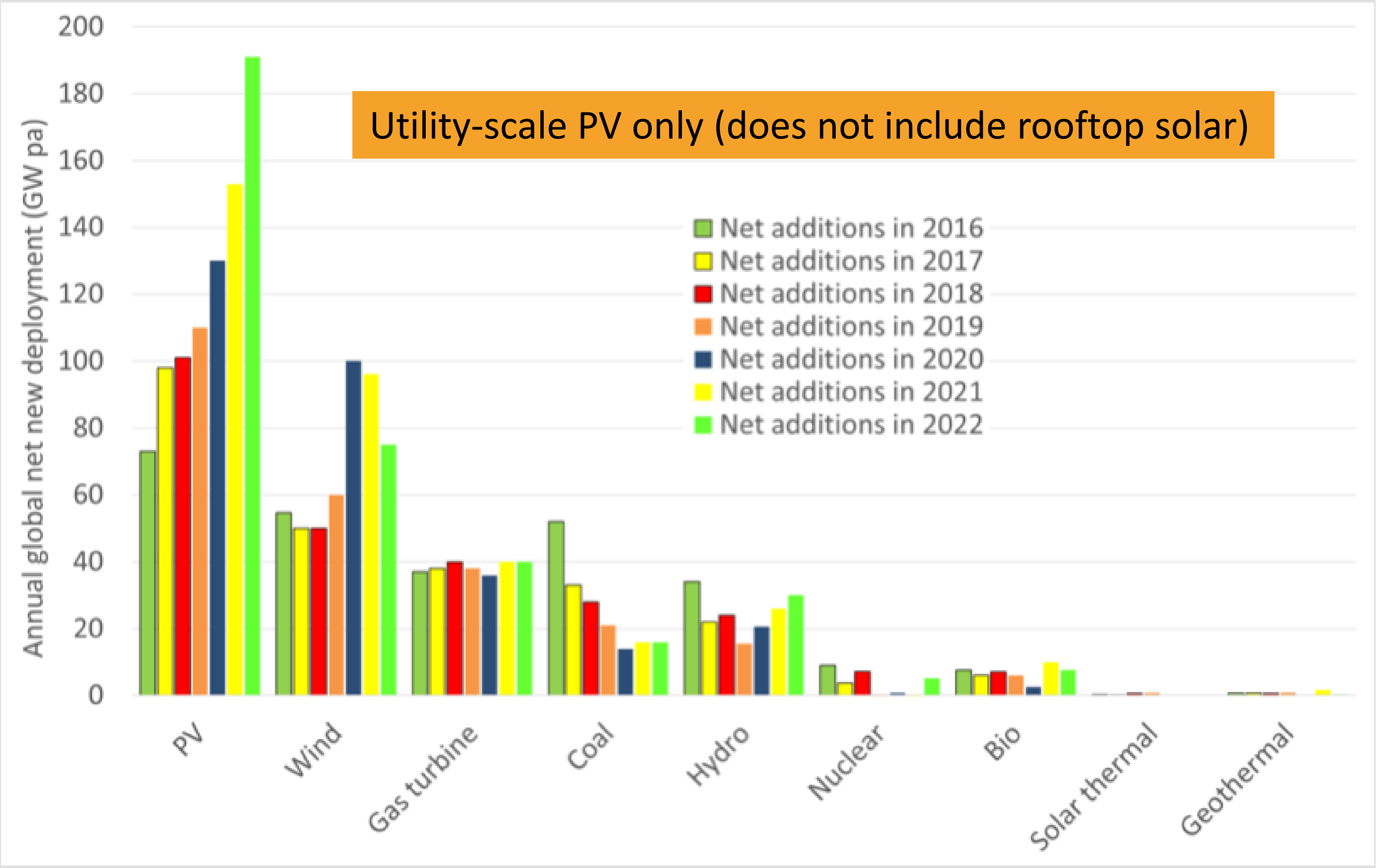
SOLAR PV IS THE FASTEST ENERGY GENERATION TECHNOLOGY WORLDWIDE



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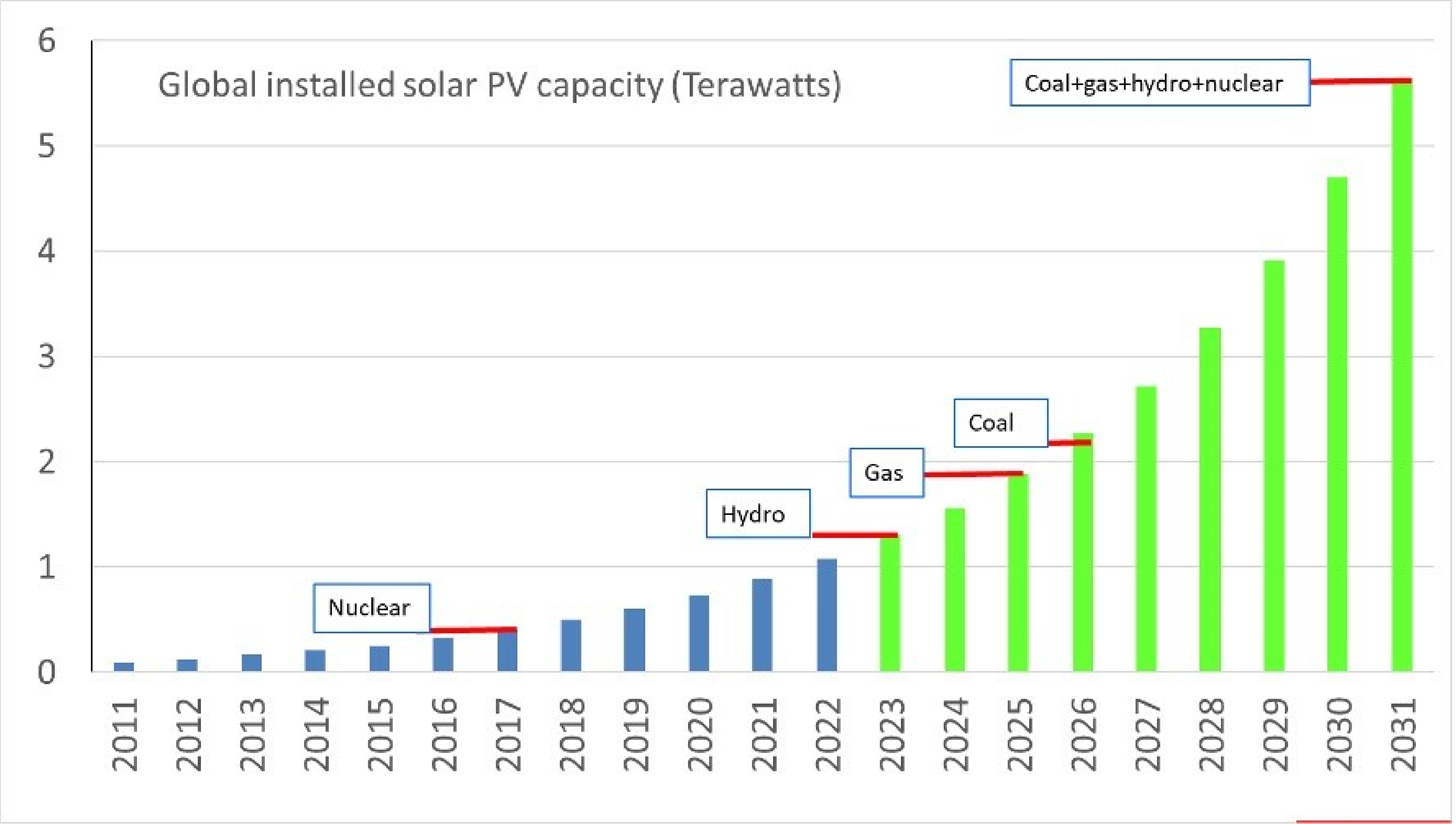
SOLAR PV IS THE FASTEST ENERGY GENERATION TECHNOLOGY WORLDWIDE



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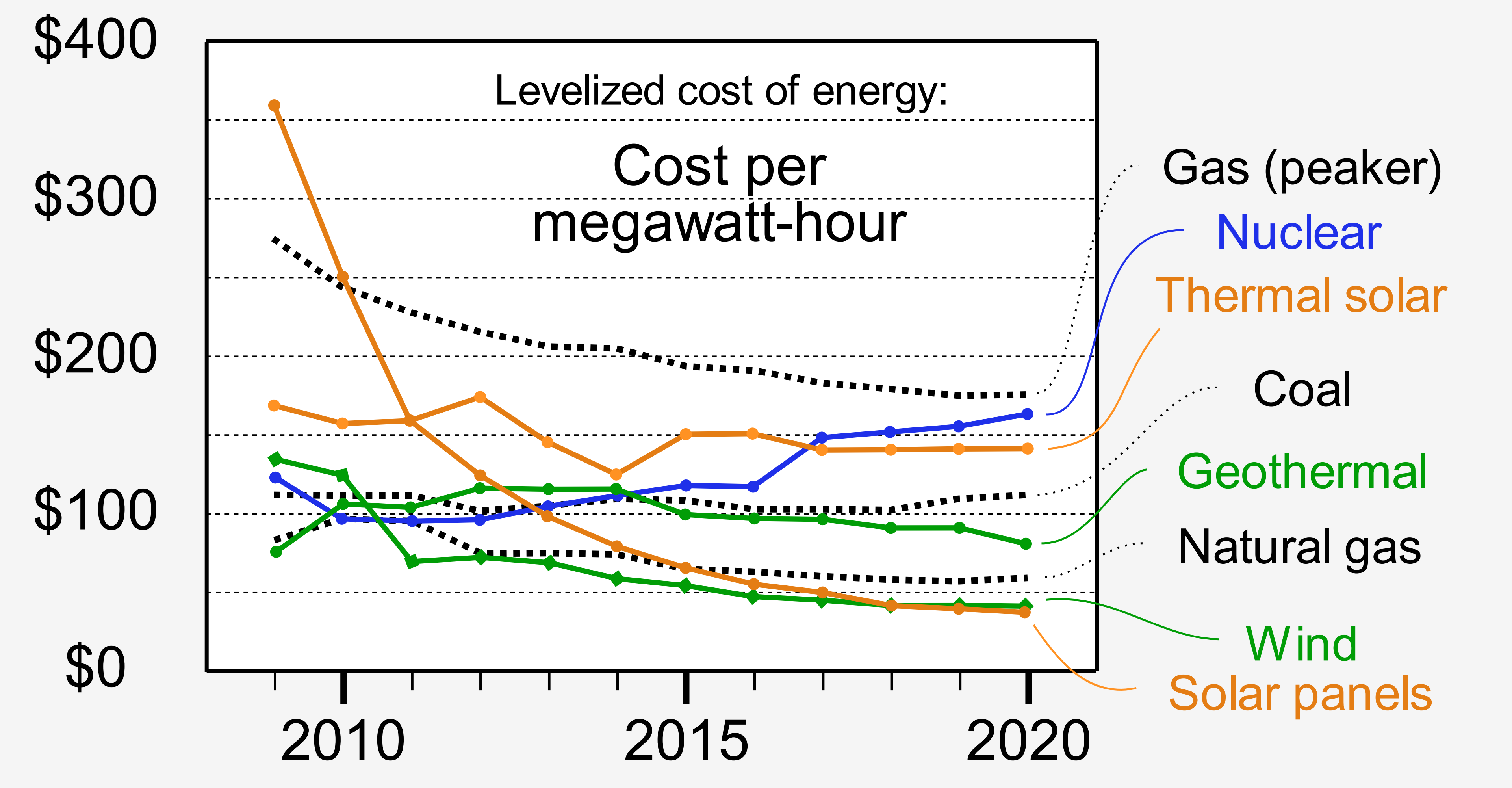
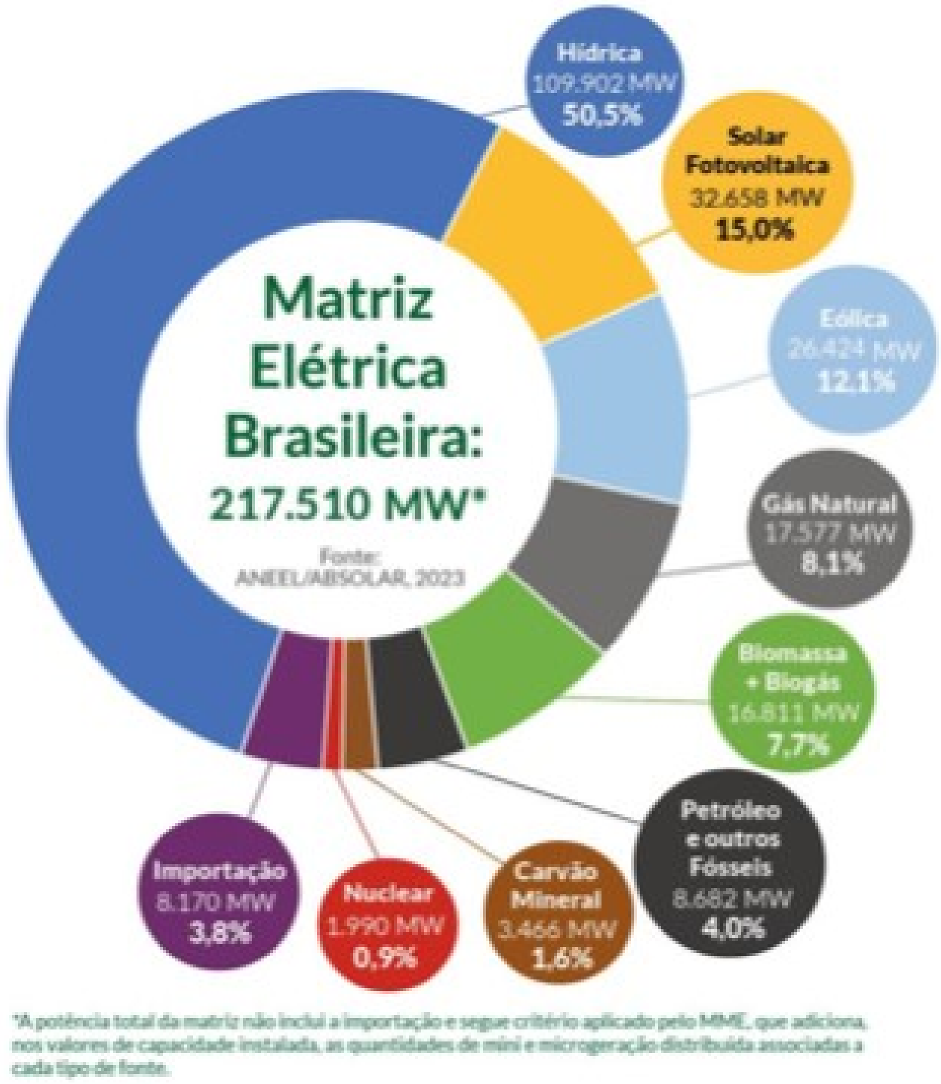
COST REDUCTION IS KEY



https://en.wikipedia.org/wiki/Cost_of_electricity_by_source

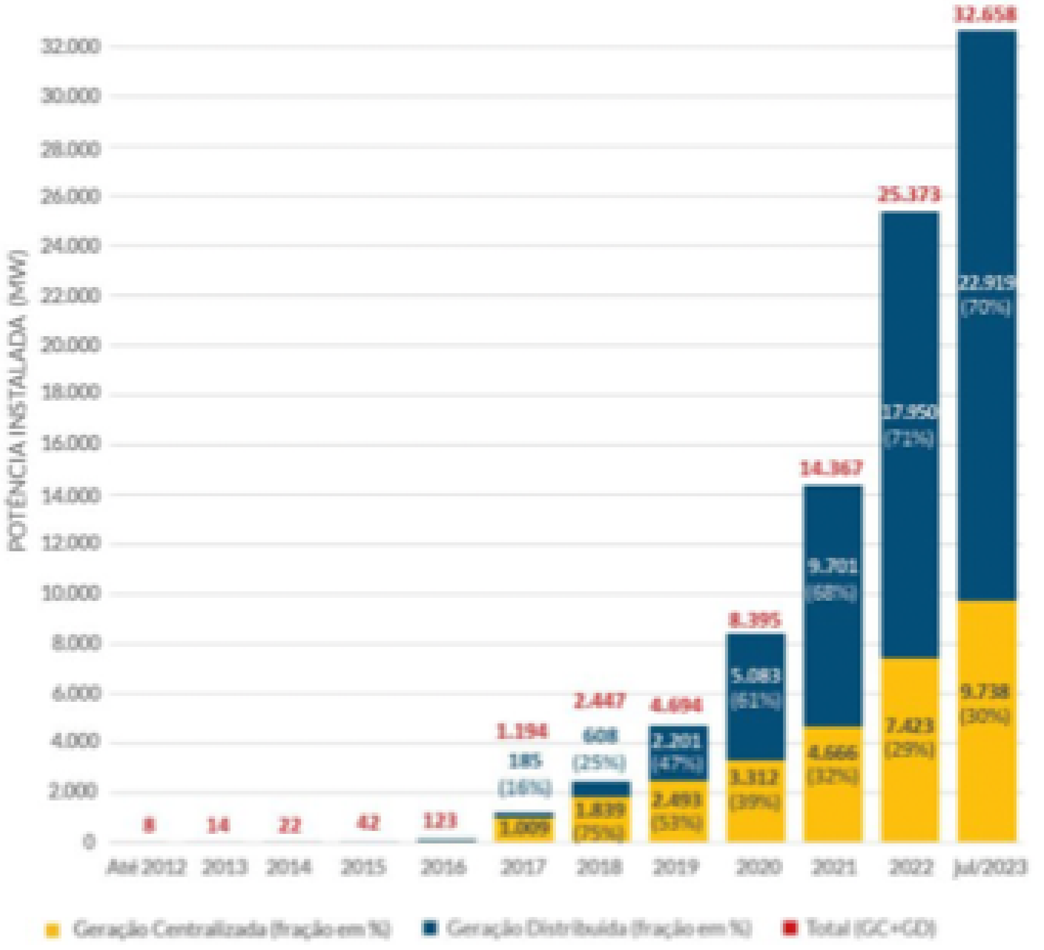
PHOTOVOLTAICS IN BRAZIL

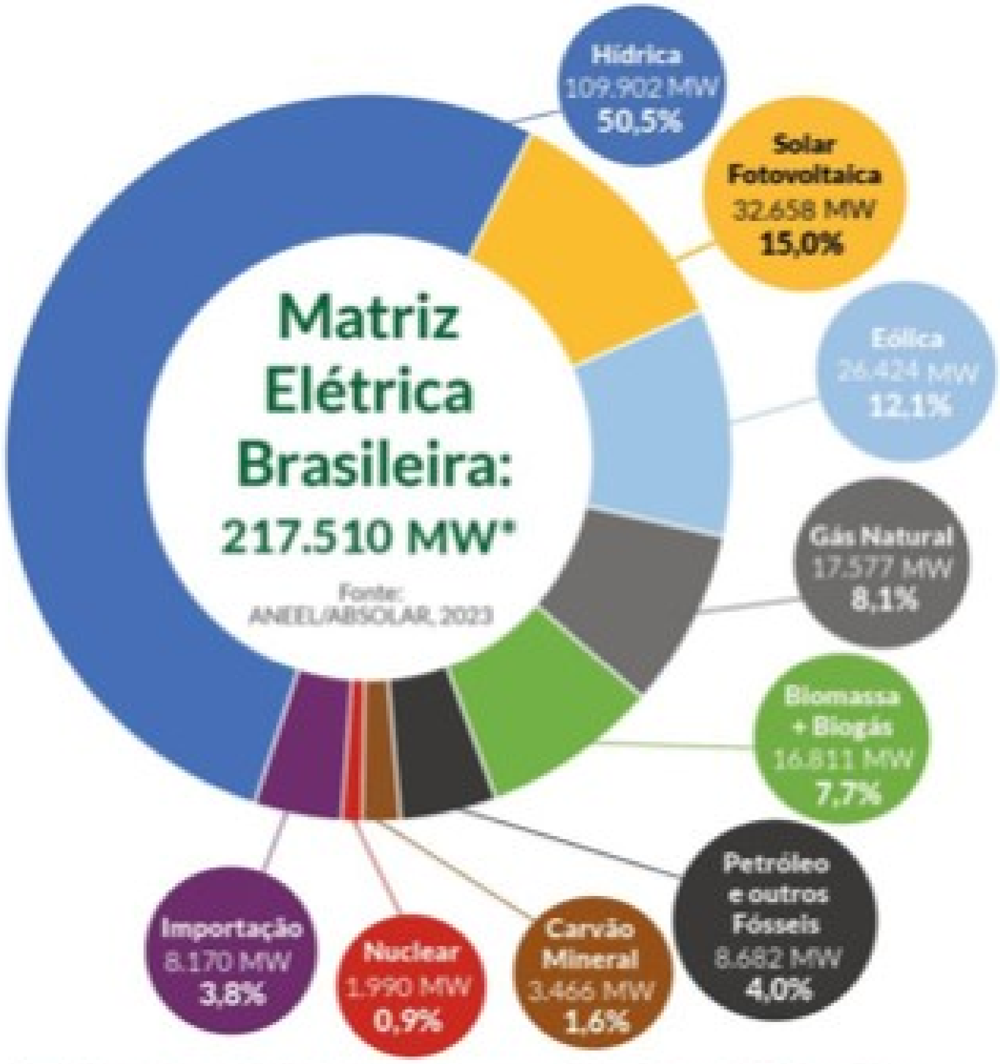


PHOTOVOLTAICS IN BRAZIL

Evolução da Fonte Solar Fotovoltaica no Brasil

Fonte: ANEEL/ABSOLAR, 2023.





*A potência total da matriz não inclui a importação e segue critério aplicado pelo MME, que adiciona, nos valores de capacidade instalada, as quantidades de mini e microgeração distribuída associadas a cada tipo de fonte.

PHOTOVOLTAICS IN BRAZIL

UNIVERSIDADE FEDERAL DE SANTA CATARINA – UFSC

40,000 STUDENTS 3,000 ACADEMIC STAFF

Aerial view of the *Universidade Federal de Santa Catarina* – Florianópolis Main Campus.
Photo by Jair Quint/Agecom/UFSC

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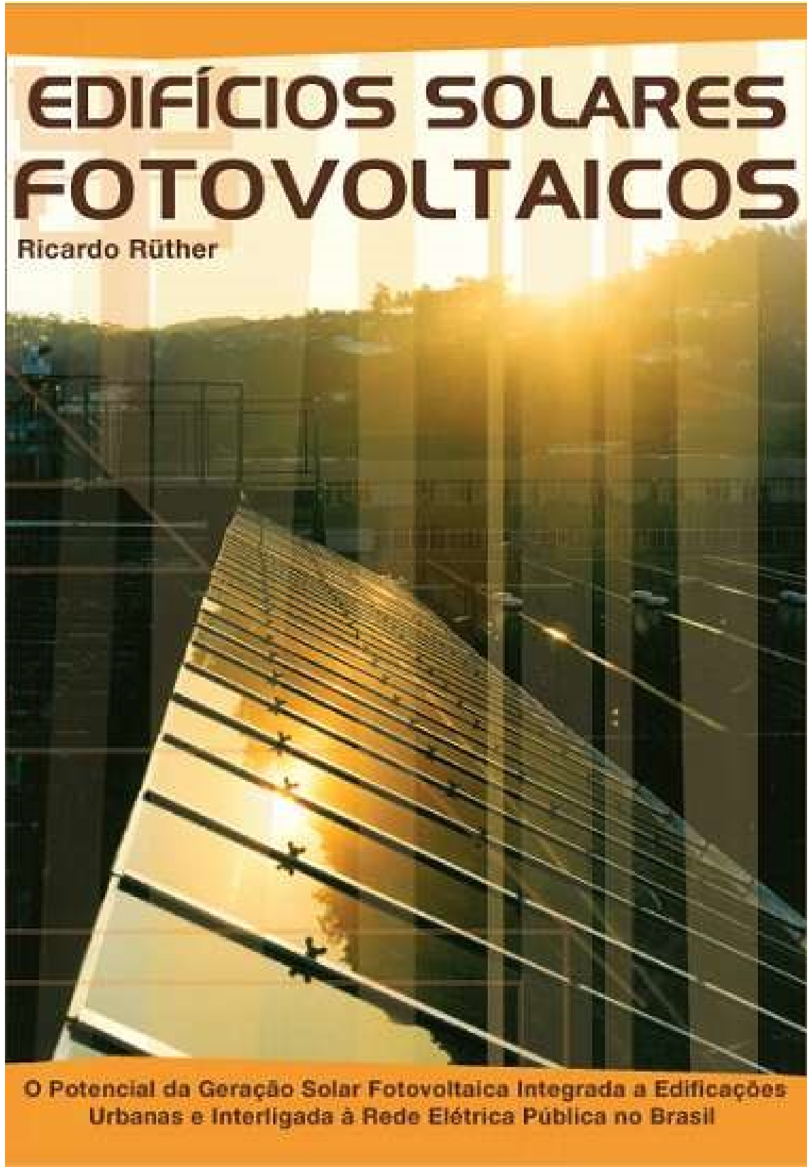
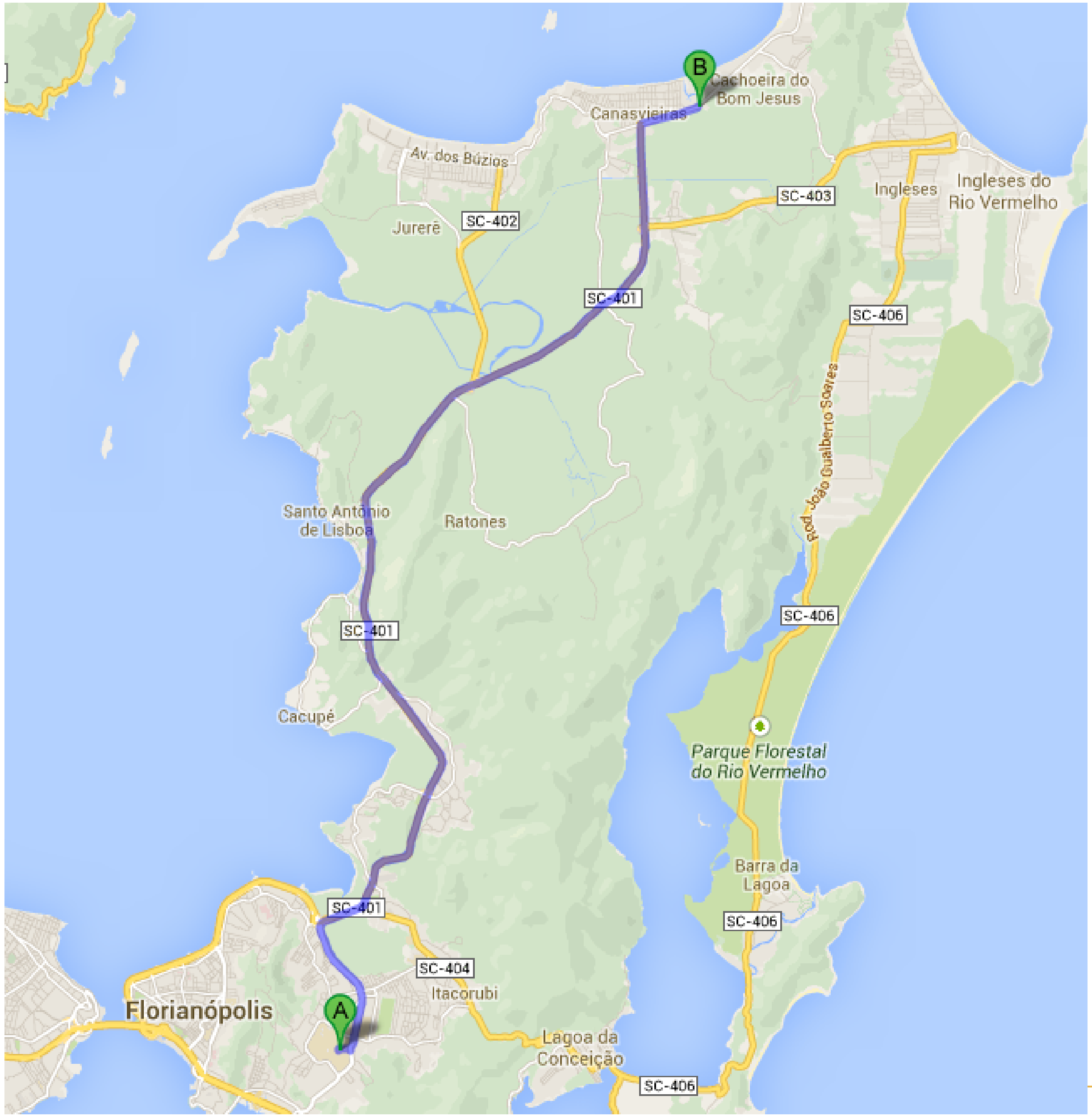
INSTALLED THE FIRST GRID-CONNECTED PV SYSTEM IN BRAZIL – SEPTEMBER 1997



R&D GRANT FROM MINISTRY OF SCIENCE & TECHNOLOGY FOR BUILDING NEW SOLAR ENERGY LAB



Moved to new Fotovoltaica/UFSC
Solar Energy Research Laboratory in 2015

25 km North of UFSC main campus

Daily routine of staff and students includes commuting back and forth between Main Campus and Solar Energy Research Laboratory

Fotovoltaica ufsc

FURTHER R&D GRANT FROM MINISTRY OF SCIENCE & TECHNOLOGY FOR DESIGNING AND BUILDING E-BUS

OUR ELECTRIC BUS HAS ALREADY TRAVELLED 120 THOUSAND KM 100% ON SOLAR ELECTRICITY

MOBILIDADE ELÉTRICA & ARMAZENAMENTO DE ENERGIA

UNIVERSIDADE FEDERAL DE SANTA CATARINA

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Electric vehicles bring new electricity demands

- Which can be fully supplied by solar PV
- 160 kWh/1000 km (6.25 km/kWh)
  = 1.6 kWp/EV = 1000 km/month
  in São Paulo
  = 15 m² carport = monthly energy needs

- Smart discharging / smart charging: vehicle-to-grid (V2G)

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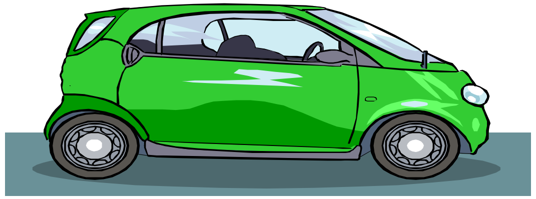
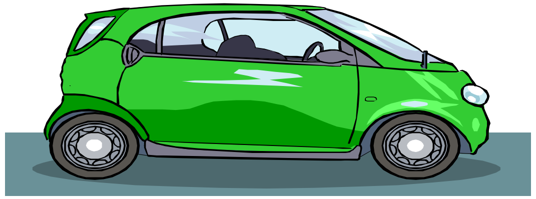
1 hectare of sugarcane ethanol yield/year
x
1 hectare of solar PV electricity yield/year



53.900 km

A *Flexfuel* car running on sugarcane ethanol will drive over 53 thousand km per hectare of sugarcane !!!

1 hectare of sugarcane ethanol yield/year
x
1 hectare of solar PV electricity yield/year

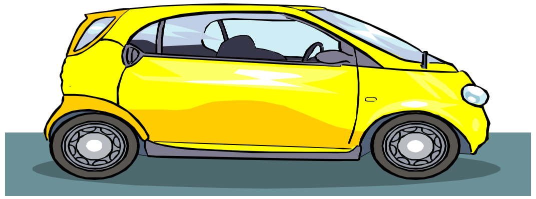


53.900 km

Flexfuel

Ethanol drive

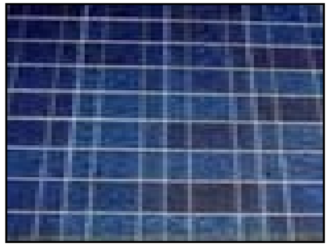
Compact car



Electric vehicle

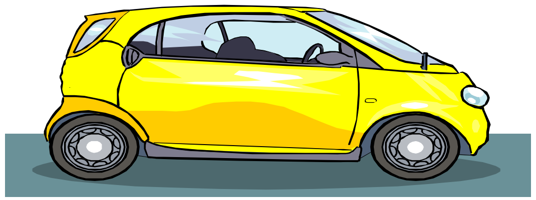
Driving on solar PV

produced electricity



3.000.000 km

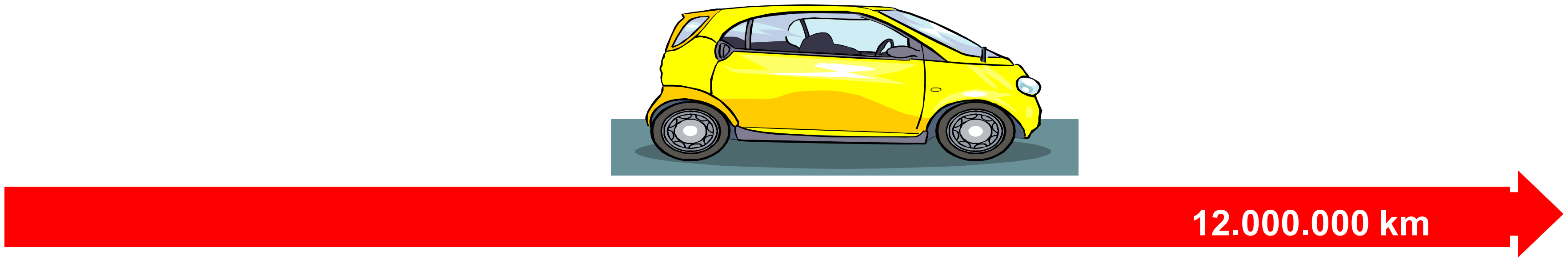
1 hectare of sugarcane ethanol yield/year
x
1 hectare of solar PV electricity yield/year



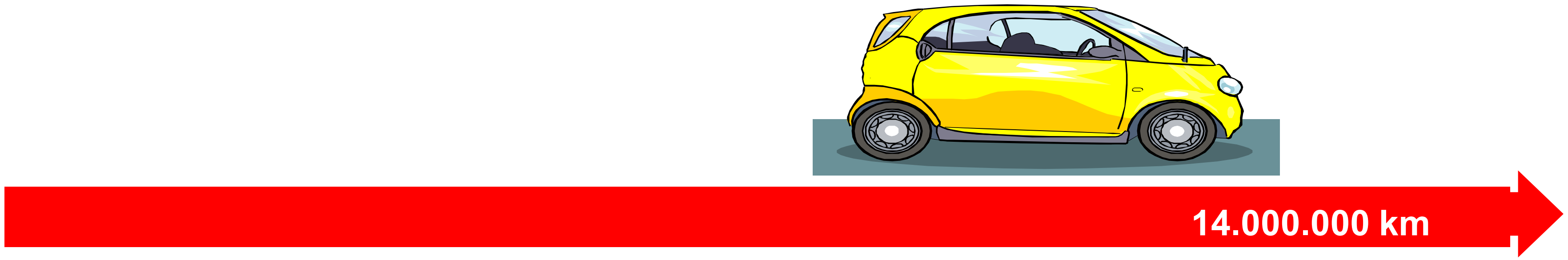
6.000.000 km

1 hectare of sugarcane ethanol yield/year
x
1 hectare of solar PV electricity yield/year

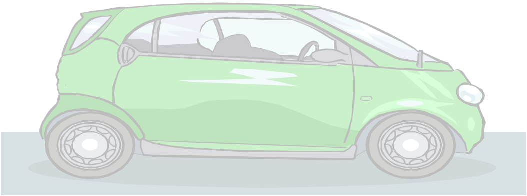
1 hectare of sugarcane ethanol yield/year
x
1 hectare of solar PV electricity yield/year



1 hectare of sugarcane ethanol yield/year
x
1 hectare of solar PV electricity yield/year



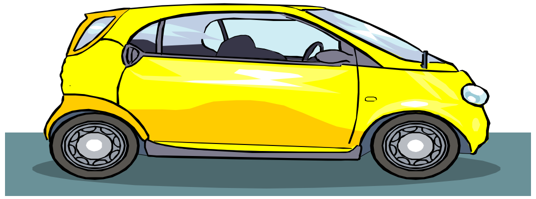
1 hectare of sugarcane ethanol yield/year
x
1 hectare of solar PV electricity yield/year



The *Flexfuel* car driving on ethanol drove ~ 1.5 times around the world

The solar PV-powered EV went

350 times around the globe!



Assumes a PV annual energy yiield of 1500kWh/kWp/year, 1,5 MWp/ha and EV using 6,25km/kWh

14.062.500 km

Li-ion Second Life Batteries

Electromobility

Discard ??

Second life use in stationary applications

Li-ion Second Life Batteries

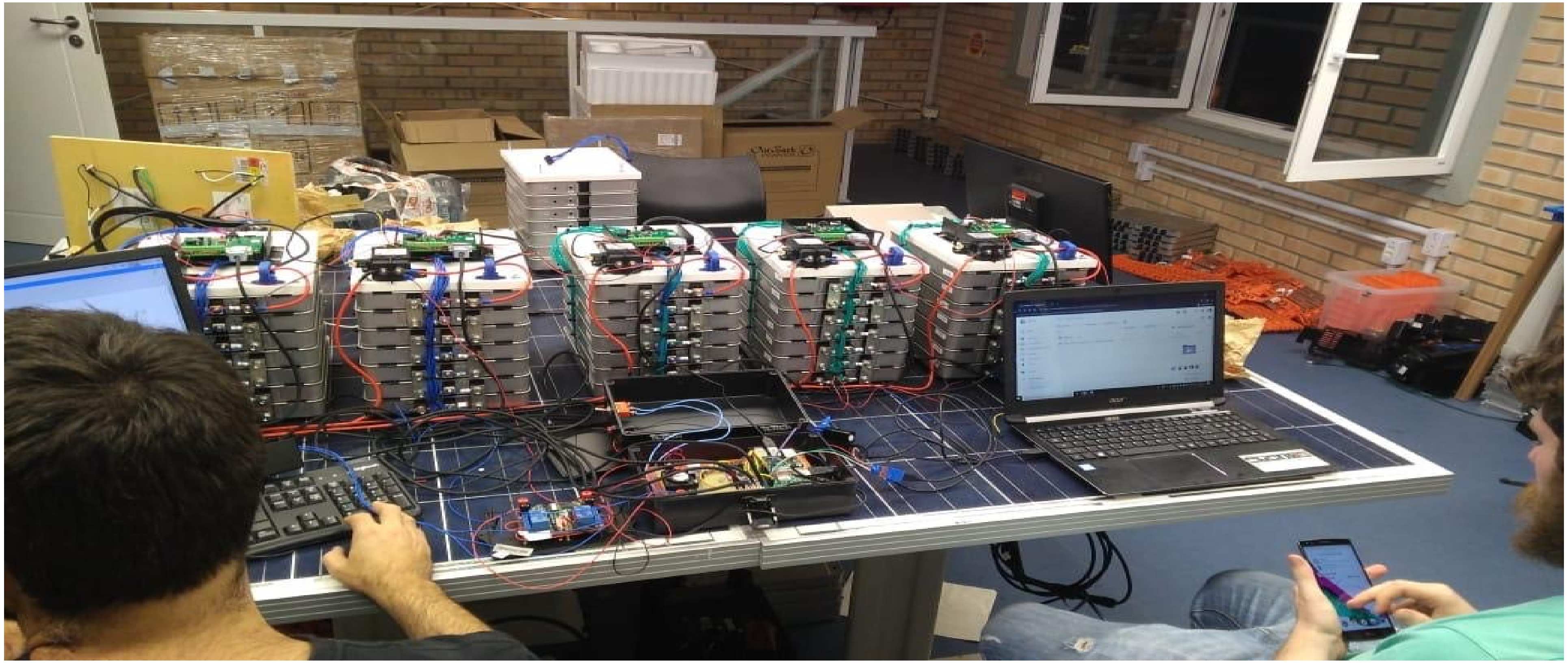
25 kWh Nissan Leaf Li-ion battery pack being repurposed for second life, stationary applications at the UFSC Solar Energy Research Laboratory

Li-ion Second Life Batteries

25 kWh Nissan Leaf Li-ion battery pack being repurposed for second life, stationary applications at the UFSC Solar Energy Research Laboratory

LI-ION SECOND LIFE BATTERIES

Second-life Li-ion batteries, recycled from electric vehicles, being repurposed for stationary applicatons at the UFSC Solar Energy Research Laboratory

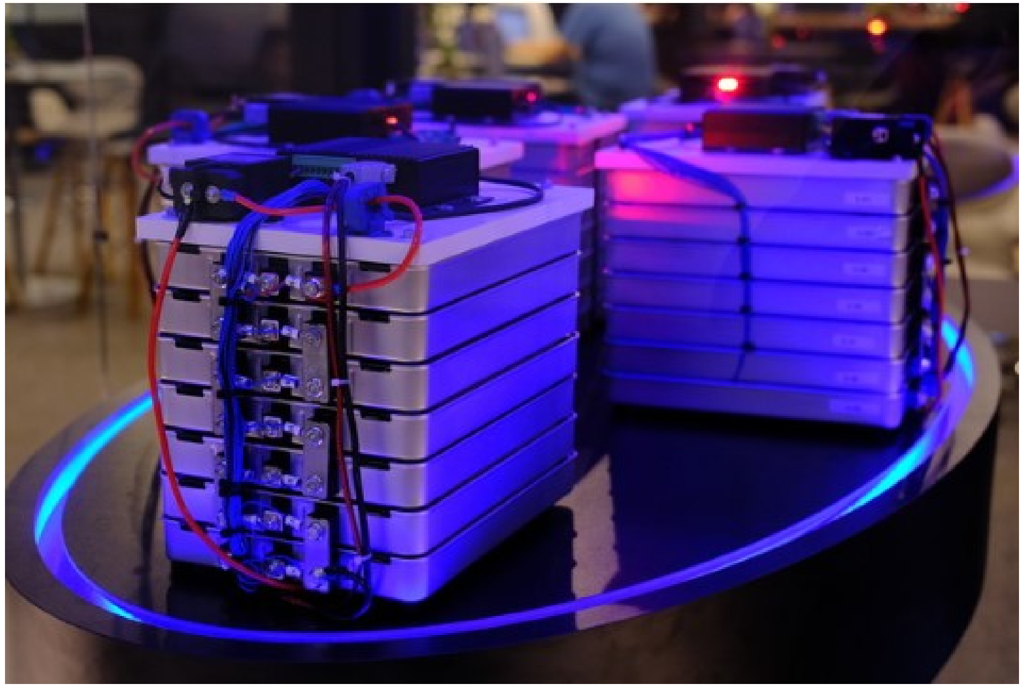


Fotovoltaica UFSC e Nissan levam baterias de lítio de segunda vida para o Salão do Automóvel 2018

07/11/2018 16:19

Notícias UFSC

O **Laboratório Fotovoltaica** da Universidade Federal de Santa Catarina (UFSC) desenvolve, de 8 a 18 de novembro, atividades com a parceira **Nissan do Brasil**, durante o **Salão do Automóvel 2018**. A empresa e a UFSC firmaram uma parceria, em agosto, para o teste de baterias de segunda vida do veículo 100% elétrico mais vendido do mundo, o Nissan LEAF.



SOLAR ENERGY RESEARCH LABORATORY
UNIVERSIDADE FEDERAL DE SANTA CATARINA

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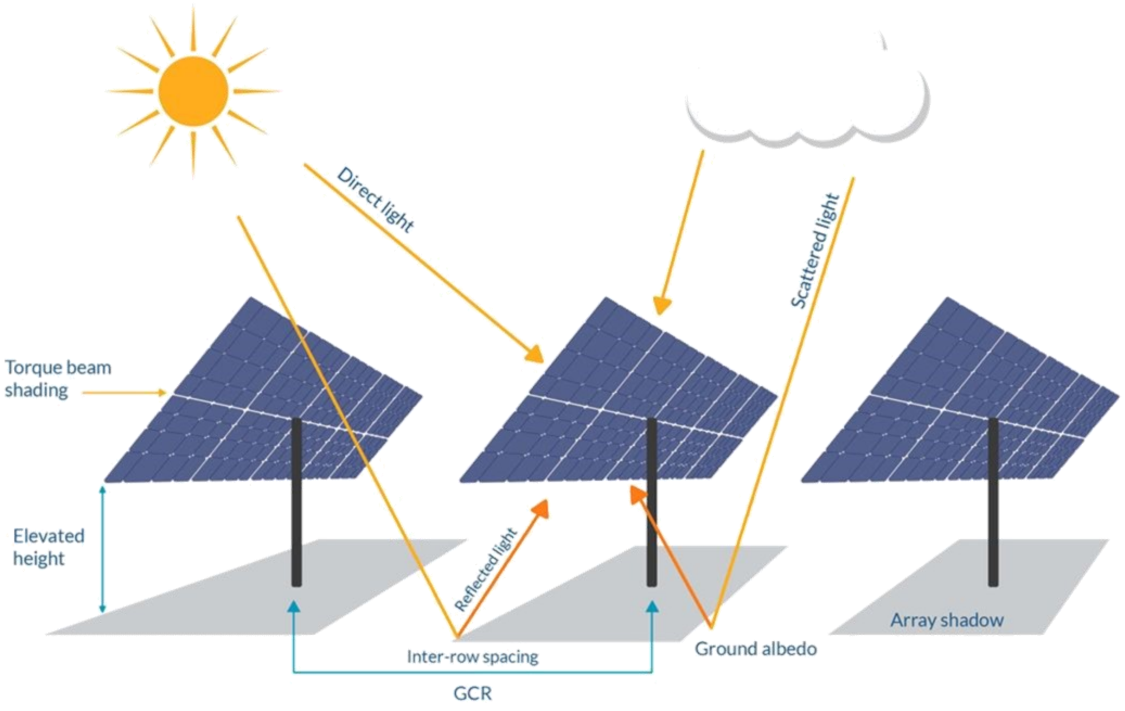
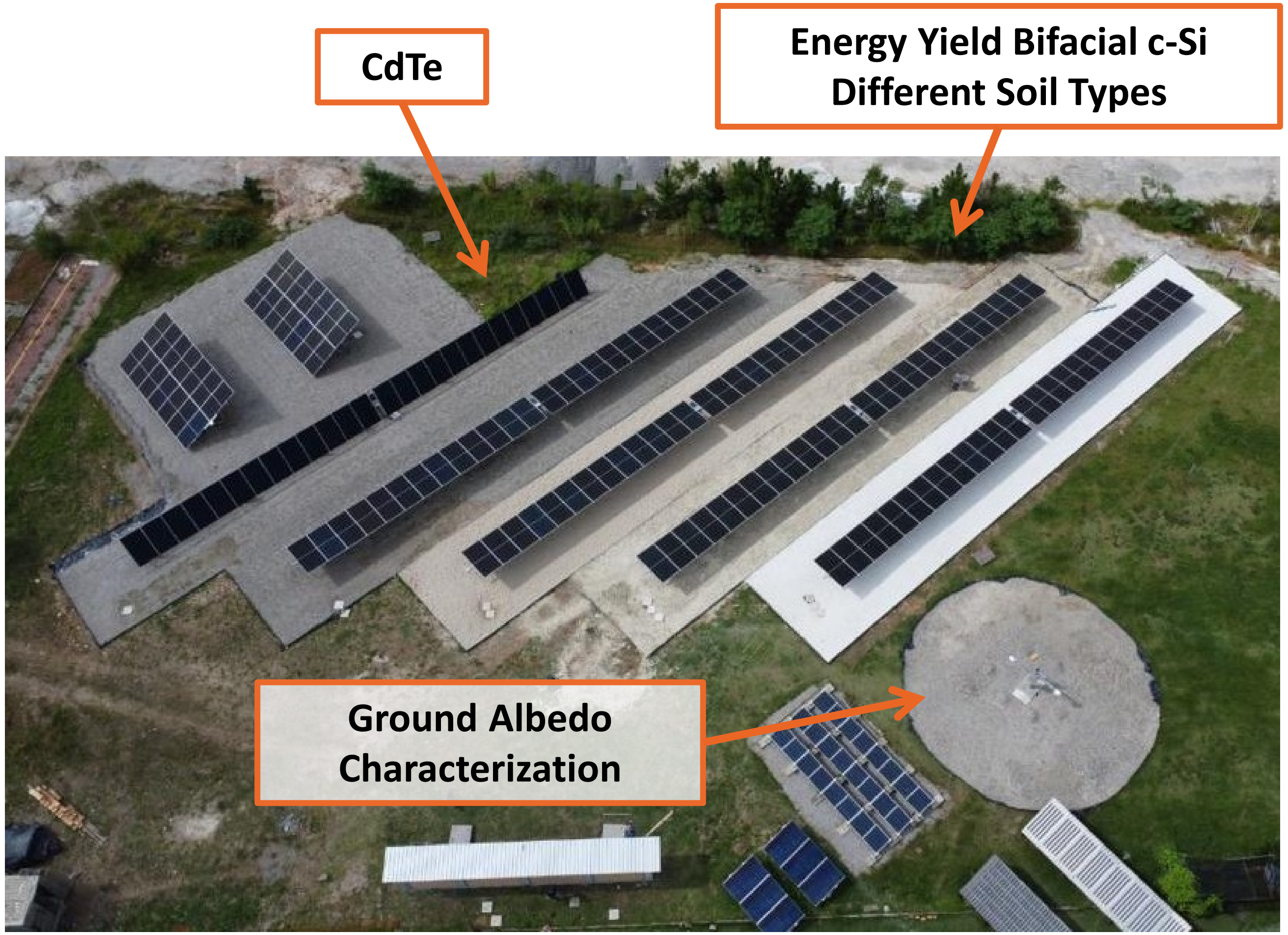


INDUSTRY PARTNERS

CanadianSolar
STInorland
HUAWEI
First Solar

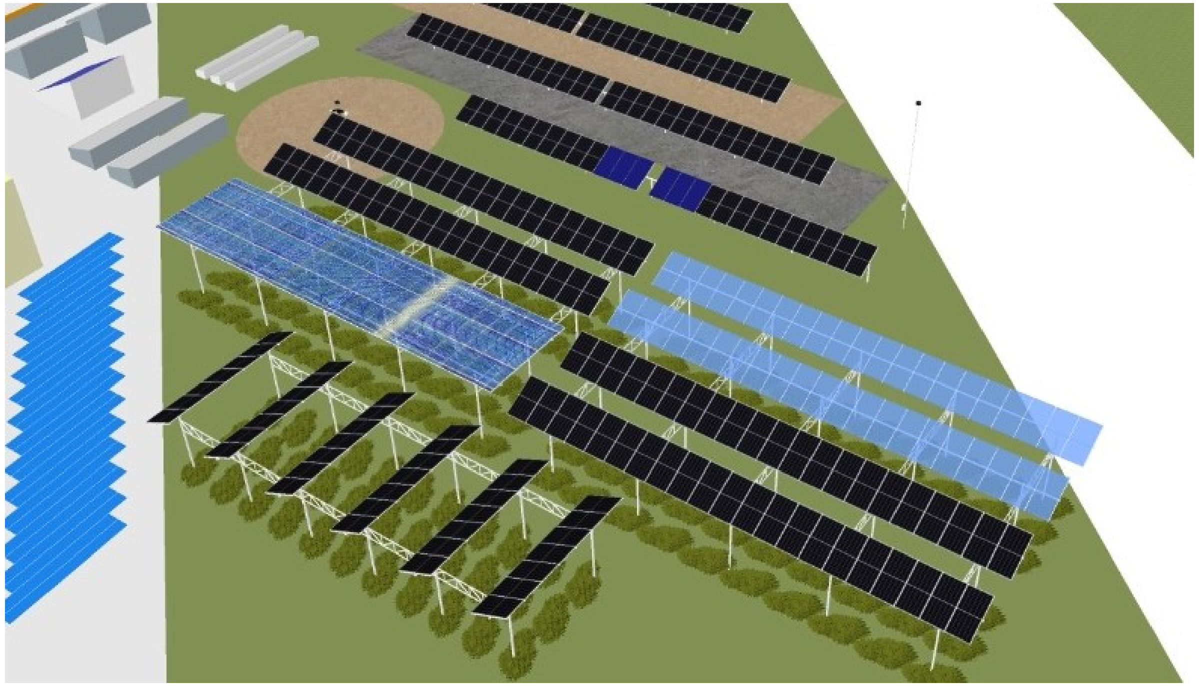


FOTOVOLTAICA/UFSC EXPANSION

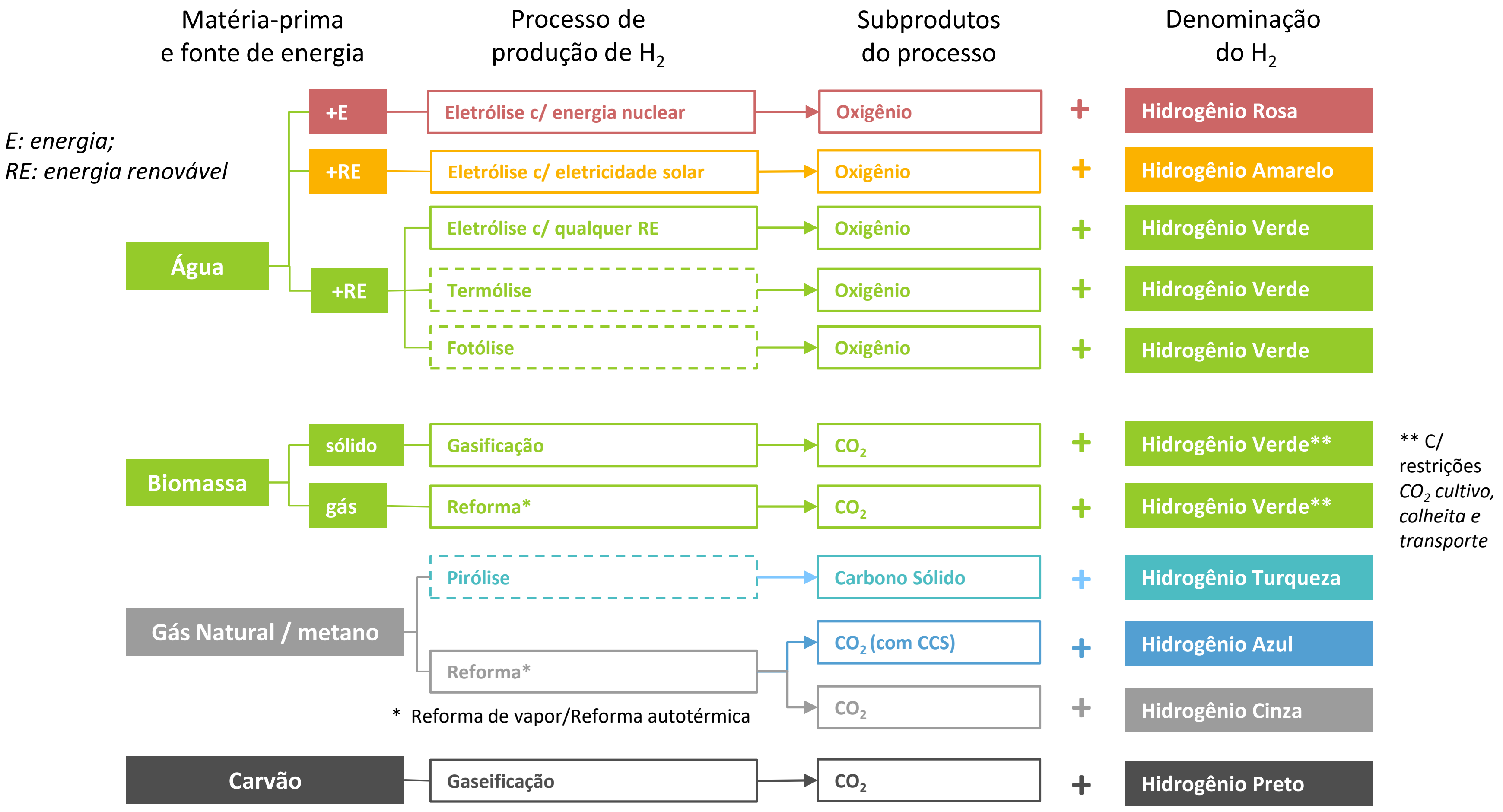
AGRIPV PILOT PV PLANT

REPSOL

AgriPV
Power Plant

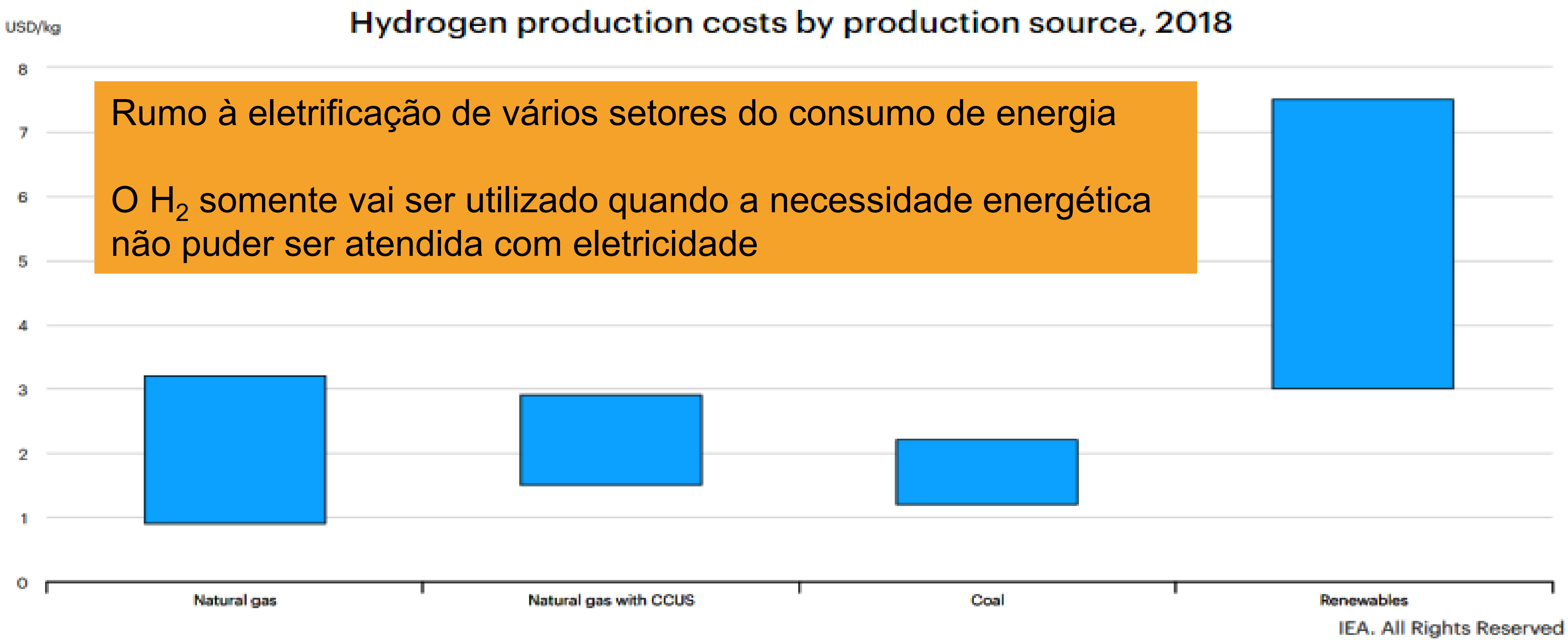


H_2: ANY COLOUR YOU LIKE



Fonte: Sachverständigenrat für Umweltfragen, Wasserstoff im Klimaschutz: Klasse statt Masse, June 2021, p.16/fig.4.

GREEN HYDROGEN: HOW EXPENSIVE?



Rumo à eletrificação de vários setores do consumo de energia

O H_2 somente vai ser utilizado quando a necessidade energética não puder ser atendida com eletricidade

- O hidrogênio já foi uma "moda" no início dos anos 2000: caro e de produção energointensiva
- Com a redução de custos da geração solar e eólica + questões ambientais, ressurgiu em 2021
- Hidrogênio verde: produzido a partir da eletrólise da água usando energia solar ou eólica

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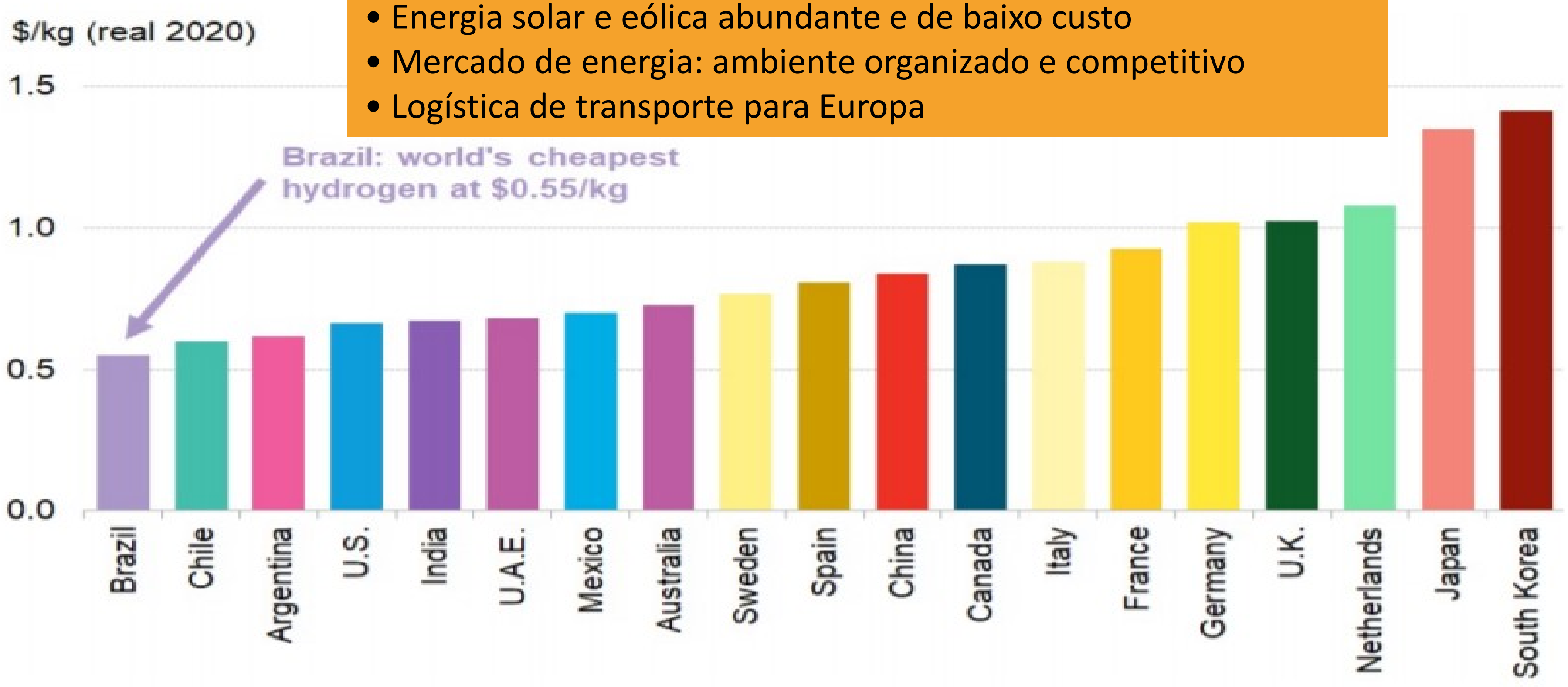
GREEN H2: HOW MUCH WILL IT COST?

Levelized cost of hydrogen production from renewables, 2050

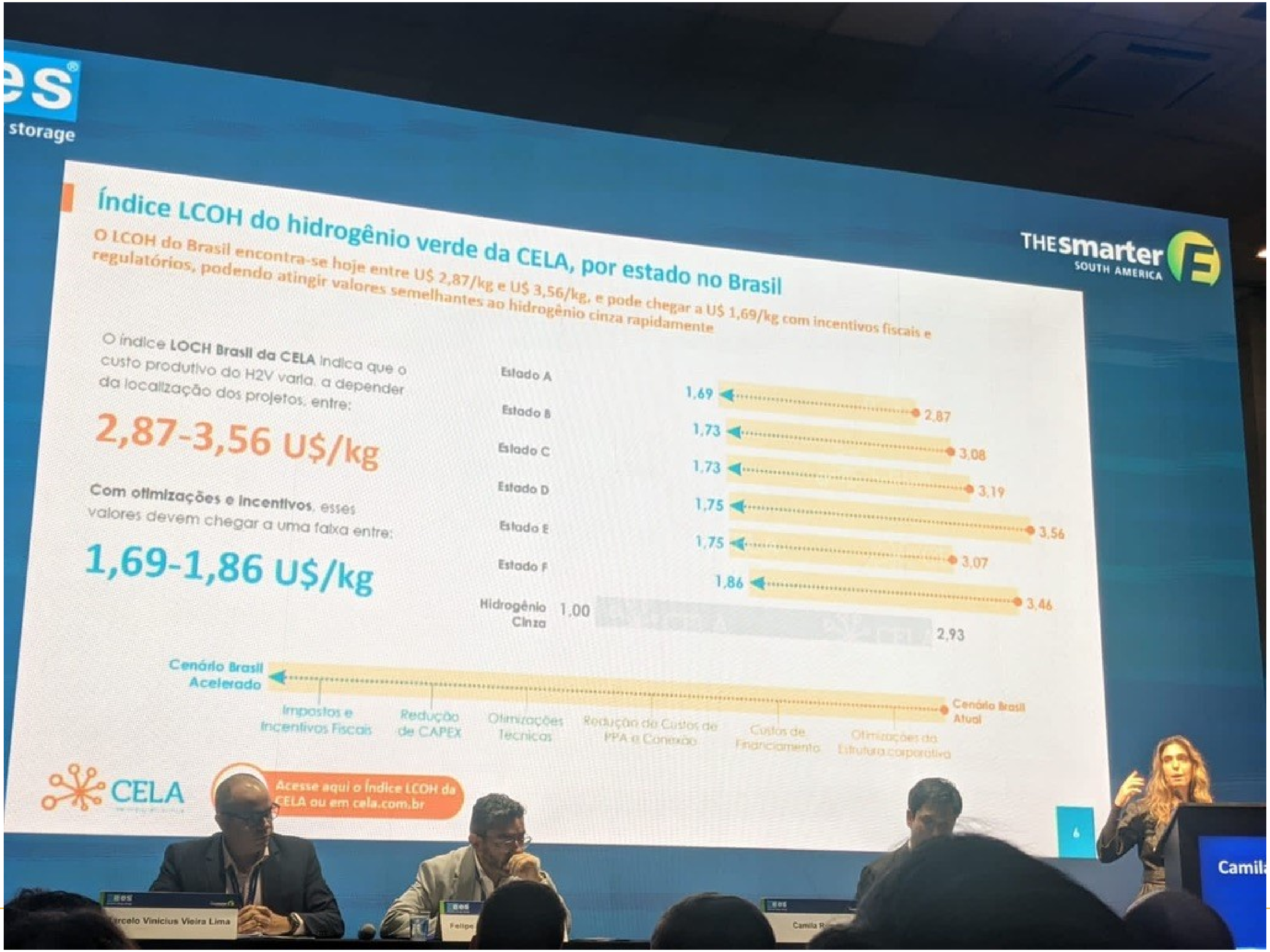
- Energia solar e eólica abundante e de baixo custo
- Mercado de energia: ambiente organizado e competitivo
- Logística de transporte para Europa



Source: BloombergNEF

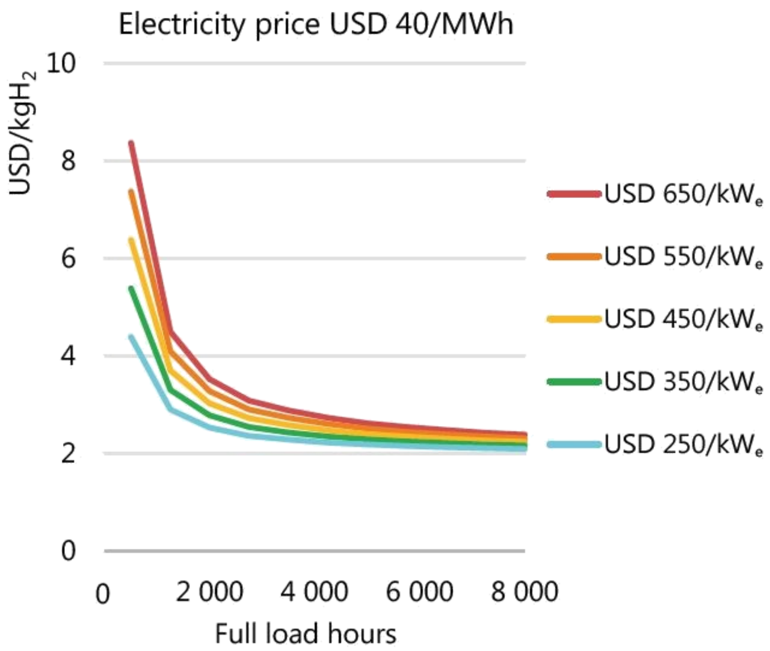
Note: Assumes our optimistic alkaline electrolyzer cost scenario and the u either solar PV or onshore wind electricity, whichever leads to the cheape hydrogen production cost.

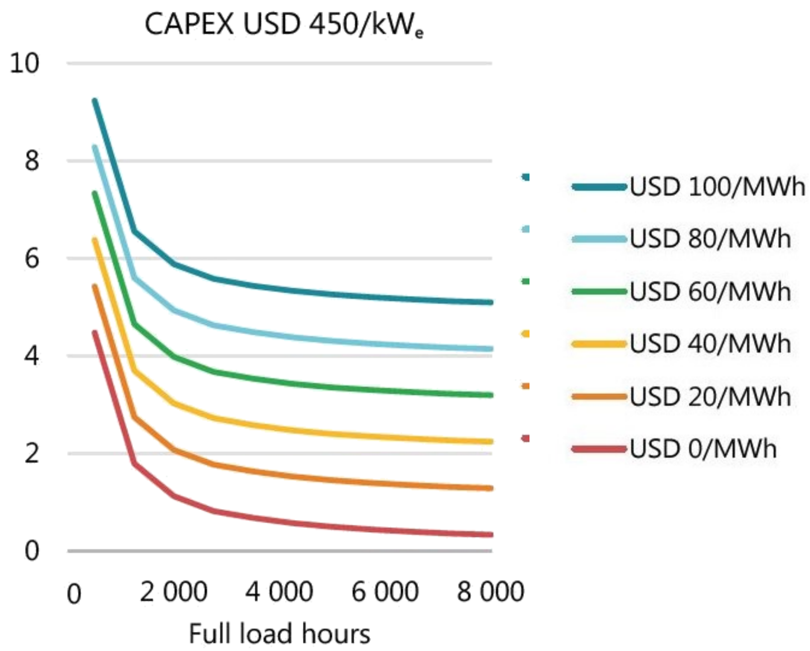
GREEN H2: HOW MUCH WILL IT COST?



CUSTO DE PRODUÇÃO DO H_2 VERDE

IMPACTO DO CAPEX, **FULL LOAD HOURS** E CUSTO DA ENERGIA ELÉTRICA





Se o FLH for alto, o custo de capital do eletrolisador não importa tanto

Os custos relativos à eletricidade importam sempre e muito

*Números baseados na eficiência do eletrolisador de 69% (LHV), taxa de desconto de 8% e durabilidade da bateria de 95.000 horas.

Fonte: IEA, The Future of Hydrogen – Seizing today's opportunities, 2019, p.47/fig.12.

Uso da "constrained off" de solar e eólica é questionável!

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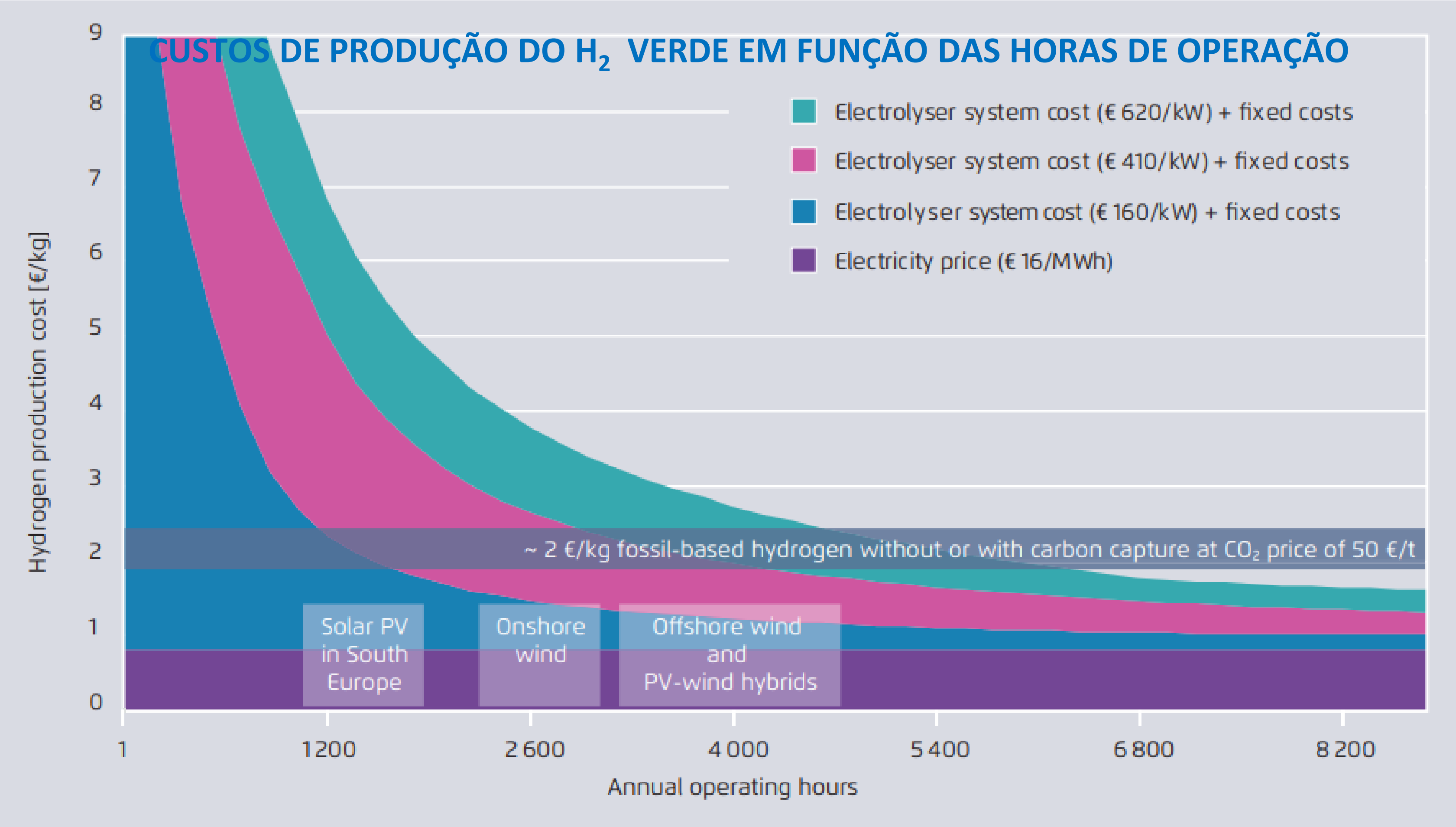
CUSTO DE PRODUÇÃO DO H_2 VERDE

IMPACTO DO CAPEX, **FULL LOAD HOURS** E CUSTO DA ENERGIA ELÉTRICA



Fonte: Agora Energiewende, Making renewable hydrogen cost-competitive, 2021, p.12/fig.2.

Hidrogênio verde, armazenamento de energia, mobilidade elétrica e energia solar fotovoltaica

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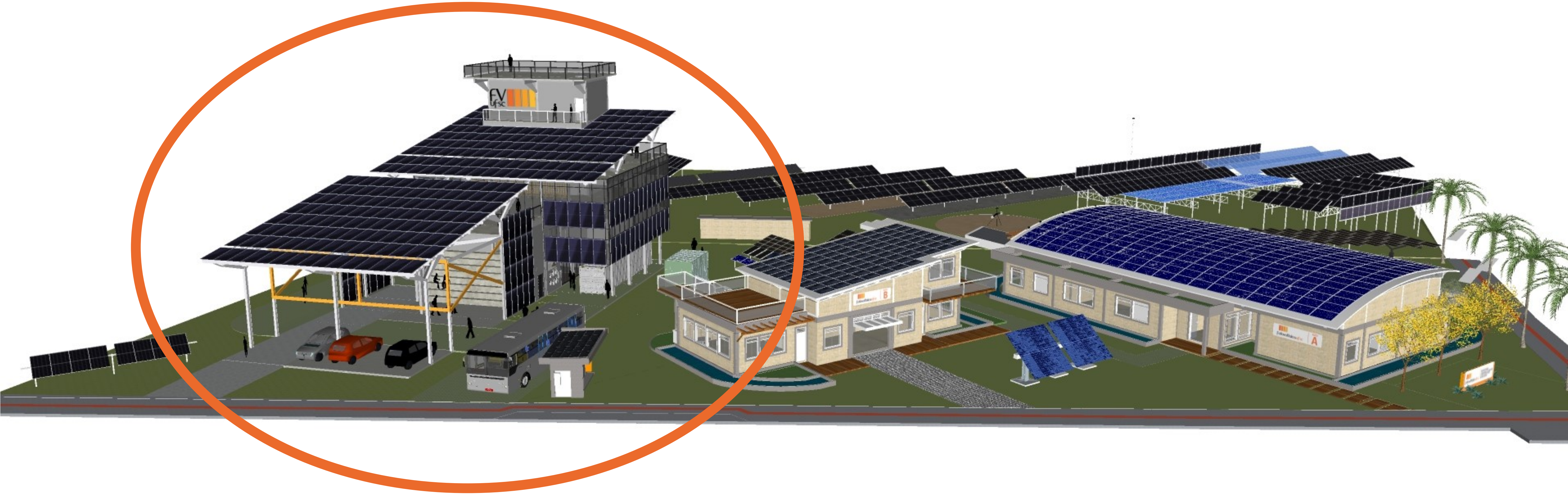
NEW BUILDING TO HOST ENERGY STORAGE LABORATORY (LI-ION BATTERIES AND GREEN H2)



NEW BUILDING TO HOST ENERGY STORAGE LABORATORY (LI-ION BATTERIES AND GREEN H2)

german cooperation
DEUTSCHE ZUSAMMENARBEIT

Implemented by

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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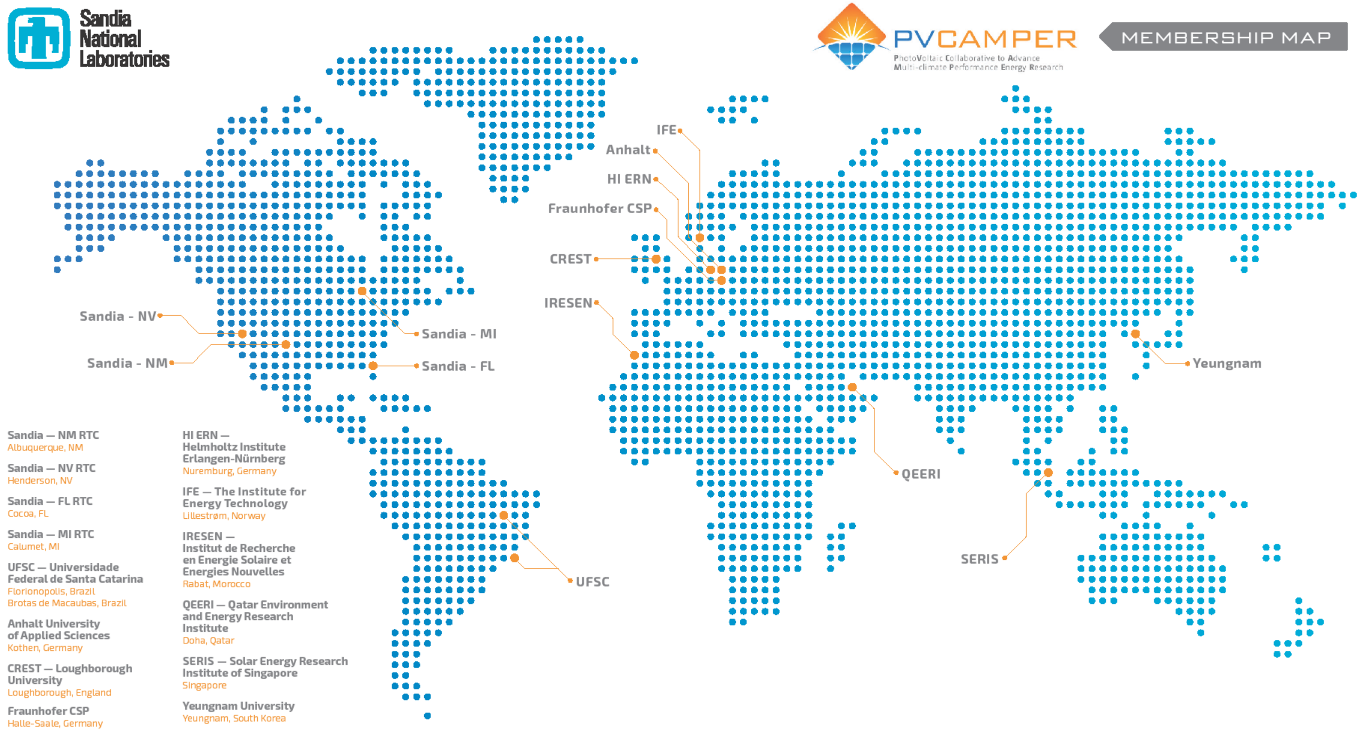
Mission:
To create a global technical platform that enables pioneering photovoltaic research, validates the performance of emerging technologies in specific climates and helps accelerate the world's transition to a solar-intensive economy



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PV CAMPER

PHOTOVOLTAIC COLLABORATIVE TO ADVANCE MULTI-CLIMATE AND ENERGY PERFORMANCE


Köthen, Germany


Kjeller, Norway


Nevada, USA


Loughborough, UK


Florianópolis, Brazil


New Mexico, USA

CAPABILITY STATEMENT

PV power plant commissioning, field performance evaluation

- Assu V – RN: 36,7 MWp
- Coremas I - PB: 31,12 MWp
- Coremas II – PB: 31,12 MWp
- Angico e Malta – PB: 63,12 MWp
- Assuruá – BA: 37,51 MWp
- Verde Vale - BA: 16,99MWp
- Apodi – CE: 162 MWp
- Anta – MG: 3,5 MWp
- UFV Campos – RJ: 510 kWp
- ANEEL – BSB: 500 kWp:
- UFV Marabá - PB: 6 MWp

389 MWp

710 MWp

- Assu V – RN: 36,7 MWp
- Coremas I - PB: 31,12 MWp
- Coremas II – PB: 31,12 MWp
- Bom Jesus da Lapa – BA: 290 MWp
- Nova Olinda – RN: 150 MWp
- Angico e Malta – PB: 63,12 MWp
- Fazenda Esmeralda – PE: 34,64 MWp
- Assuruá – BA: 37,51 MWp
- Verde Vale – BA: 16,99 MWp
- Anta – MG: 3,5 MWp
- UFV Campos – RJ: 510kWp
- ANEEL – BSB: 500kWp:
- Canas - SP: 3,17 MWp
- Lapa – BA: 1,24 MWp
- Presidente Alves – SP: 3,9MWp
- Marabá - PB: 6 MWp

PV power plant monitoring Contractual energy output, performance assessment

PV project output certification, PV power plant due diligence

- Tauá – CE: 40 MWp
- Rancharia – SP: 23,52 MWp
- Condado – PB: 29,4 MWp
- Assu V – RN: 36,7 MWp
- João Dourado – BA: 375,6 MWp
- Carnaúbas – RN: 64,85 MWp
- Várzea de Palma – MG: 64,36 MWp
- Paranaíba – MS: 83,14 MWp
- Bom Jesus da Lapa – BA: 290 MWp
- Nova Olinda – RN: 150 MWp
- Serra do Mel – RN: 1297 MWp
- Rovema – SISOL: 33,9MWp / 81MWh

2488 MWp

81MWh

CAPABILITY STATEMENT – PV PROJECT CLIENTS

CTG Brasil	CARBON TRUST	Celesc	ENGIE	Eternit	FIEC
fundoverde UFRJ	giz	DRESSER-RAND Guascor	IBRAP ALUMÍNIO E PLÁSTICO	Intertechne	KYOSERVICE
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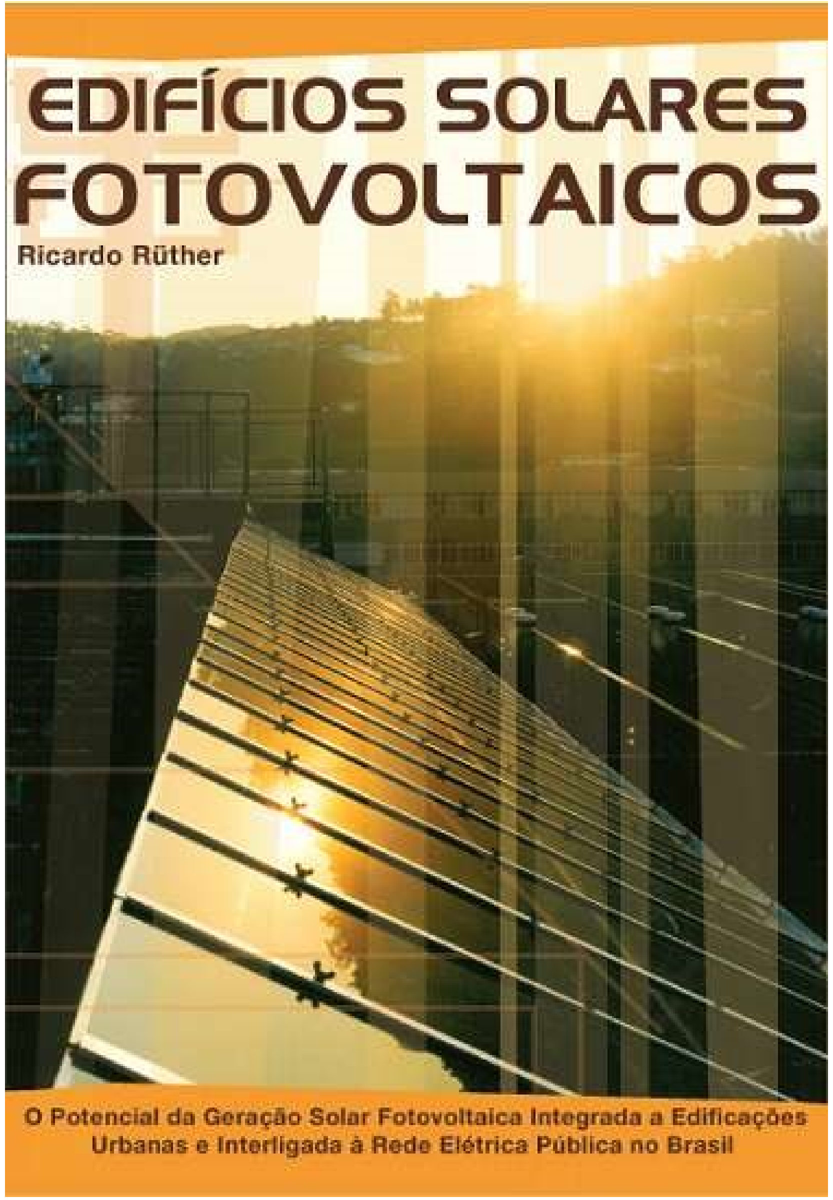
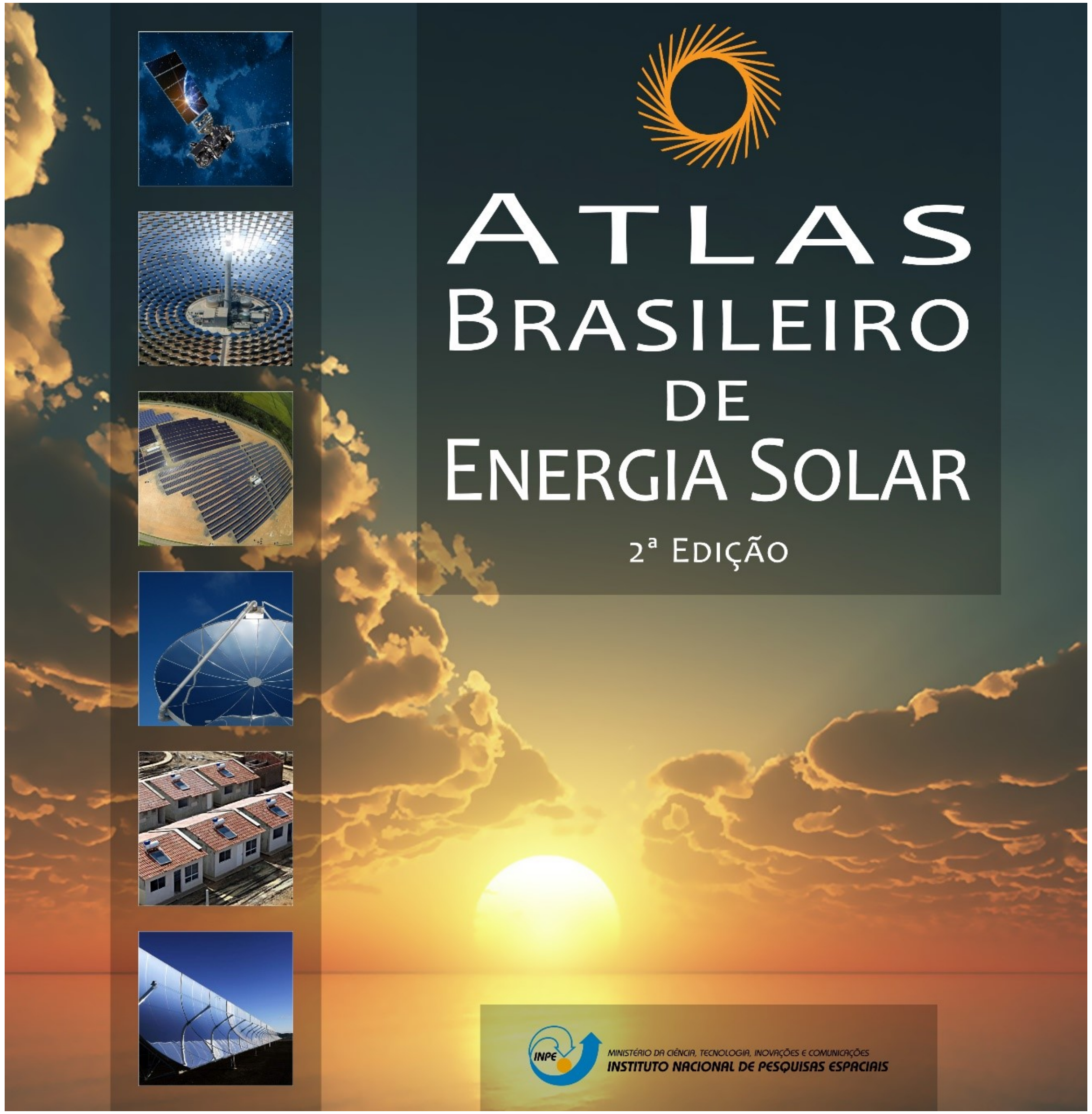
SOLATIO ENERGIA PROJECT MANAGEMENT	TECNOVA RENOVÁVEIS Integrando Soluções	Statkraft	WEG	TECNOVA ENERGIA	C40 CITIES

CAPABILITY STATEMENT – DISTRIBUTED GENERATION AND SOLAR RESOURCE ASSESSMENT COOPERATION WITH INPE





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CAPABILITY STATEMENT – INTERNATIONAL COOPERATION (PVCAMPER)

PhotoVoltaic Collaborative to Advance Multi-climate Performance Energy Research

(PV CAMPER)

Overview

Formed in 2018, PV CAMPER is an international community of research institutions committed to sharing high-fidelity meteorological and performance data in order to advance photovoltaic (PV) research and expand solar markets. To date, PV CAMPER has 10 members and a network of 13 field sites that span both hemispheres and most major climate zones.

Technical Objectives

Accelerating solar capacity worldwide requires confidence in 1) the cross-climate performance of emergent, high-efficiency PV technologies, 2) the accuracy of irradiance and other sensor measurements needed for yield comparison and simulations and 3) the identification of local environmental contributors to long-term reliability. To help meet these challenges, PV CAMPER aims to:

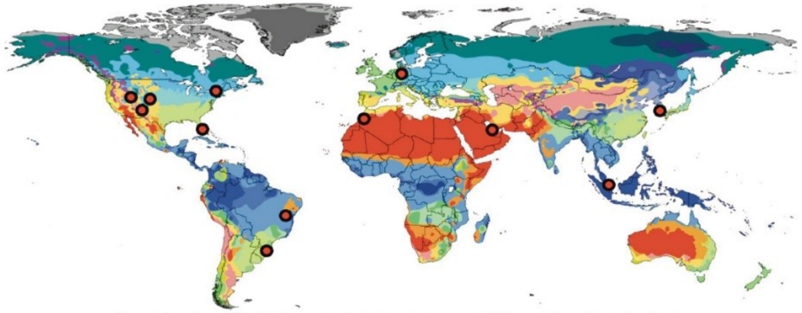

Figure 1. Location of PV CAMPER member institutions is shown on this Köppen-Geiger climate classification map.

Each member institution operates one or more field laboratories and is actively engaged in PV performance and reliability research. To facilitate collaboration and ensure data quality across all sites, PV CAMPER representatives have agreed to deploy similar instrumentation, methods of data collection, and O&M protocols. The result is a global network of outdoor laboratories that can be leveraged for research investigations ranging from experimentation to simulation and validation studies.

- Foster collaborative R&D in the areas of PV performance-validation and reliability
- Provide a global platform for evaluating emerging, high-efficiency PV technologies and for identifying and quantifying the factors that contribute most to climate-specific efficiencies
- Generate a set of best practices with respect to data collection; quantify and reduce measurement uncertainties and increase the accuracy and global applicability of performance models
- Develop a technical basis for matching new technologies, including novel cell and module types, to their operating environments (spectral sensitivities, irradiance characteristics, temperature range, etc.)

Figure 2. Images of irradiance sensors at three field sites: (clockwise from top left) POA pyranometer and reference cells on baseline system in Vermont, USA; POA pyranometer and PV-modules in Halle, Germany; GHI and DNI sensors in Köthen, Germany; irradiance sensors in Florianopolis, Brazil; (above) albedometer in Vermont.

Membership Requirements

PV CAMPER is an expandable organization and welcomes new members willing to meet the organization's high standards for data quality and availability. To that end, each member institution must maintain an outdoor field laboratory with the following technical capabilities:

- Grid-tied crystalline-silicon reference system for cross-site data analysis and to establish a baseline against which other technologies can be compared;
- High-accuracy meteorological instrumentation to measure multiple irradiance levels (DNI, GHI, DHI, POA and albedo), precipitation, relative humidity, ambient air temperature and wind-speed and direction);
- Soiling measurement station;
- High-resolution DC data-monitoring instrumentation to measure PV system performance;
- High-frequency data acquisition systems for both meteorological and PV performance data;
- Module characterization capabilities that meet IEC standards (solar simulator and EL imaging capabilities).

PV CAMPER members must sign a Memorandum-of-Understanding and agree to:

1. Transmit data daily to a cloud database, where it can be accessed by members of the collaborative;
2. Adopt PV CAMPER baseline characterization and O&M protocols;
3. Participate in PV CAMPER collaborative R&D;
4. Attend regular conference calls and at least one annual face-to-face meeting.

Partner Organizations

Value to the Global Photovoltaics Community

PV CAMPER's network of research institutions reflects a common goal: the desire to foster and grow a community that can help transition the world to a more solar-intensive future. Collectively, this organization offers:

- Repository of high-fidelity meteorological and PV performance data from geographically and climatically diverse sites
- Broad expertise in such areas of PV research as soiling-losses, uncertainty drivers (cloud persistence, moisture, airborne particulates) and spectral responsiveness
- Data to support the design and optimization of PV systems for specific operating environments, helping increase markets and expand the solar industry

Founding Members

- **Brazil: Universidade Federal de Santa Catarina (UFSC)**
  Ricardo Rüther
- **Germany: Anhalt University of Applied Sciences**
  Sebastian Dittmann
- **Germany: Fraunhofer Center for Silicon Photovoltaics (CSP)**
  Ralph Gottschalg
- **Morocco: Institut de Recherche Energie Solaire et Energie Nouvelle (IRESEN)**
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- **South Korea: Korea Testing Laboratory (KTL)**
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CAPABILITY STATEMENT – CUTTING EDGE APPLIED R&D ON UTILITY-SCALE PV POWER PLANTS

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Assessing the influence of solar forecast accuracy on the revenue optimization of photovoltaic + battery power plants in day-ahead energy markets

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ARTICLE INFO

Keywords:
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Energy storage
Renewable energy
Battery systems

ABSTRACT

Energy storage has become a subject of great interest in the last years due to the increasing penetration of non-dispatchable renewable energy power plants, especially solar photovoltaics (PV) and wind. Energy storage systems can add value to the grid in many ways: energy schedule optimization, ancillary services, renewable energy integration at high penetration levels, and so on. However, from the perspective of the asset's owner, it is important that the system regulator provides a regulatory framework and energy prices that stimulate the private plant operator to dispatch its energy storage system to assist the grid and get rewarded by these operations. An optimization problem is presented from the perspective of an asset owner with a PV plant and battery energy storage system. From this perspective, the agent must know the day-ahead spot-market energy prices and predict the day-ahead PV generation to decide on how to dispatch the battery system. We have evaluated 11 forecast accuracies to assess how the forecast accuracy can impact on the agent's total revenue.

The findings showed that, if the agent's objective is to use the battery system only to guarantee the contracted energy, the battery system does not add as much value as it could; and higher forecast uncertainties lead to higher revenues, because the battery will then operate closer to the tariff arbitrage strategy, which is the optimal strategy for battery dispatch, independent of PV generation, relying only on the spot-market energy prices.

1. Introduction

Battery energy storage systems (BESS) have become a subject of great interest in recent years due to the their rapidly declining prices, and the increasing penetration of non-dispatchable renewable energy power plants such as solar photovoltaics (PV) and wind. BESS have already been proved to be a valuable asset in many situations [1], by mitigating curtailment losses in non-dispatchable RE sources [2–4], operating in spot market using tariff arbitrage strategies [5–7], participating in reserve markets [8] and ancillary services [9]. However, from the perspective of the asset's owner, it is important that the current regulation provides a regulatory framework and energy prices that stimulate the private plant operator to dispatch an energy storage system to assist the grid and get rewarded by these operations. McPherson et al. [10] presented a review on electricity market rules and show that spot market prices and the market design can significantly change the dispatch strategy.

The optimal dispatch of energy storage systems has been studied in a variety of situations, with special emphasis on integrated renewable energy applications. Sahoo and Hota [11] developed a bidding strategy for a microgrid with renewable energy and energy storage using Improved Whale Optimization Algorithm (IWOA) for maximizing the profit, and taking the uncertainties with the renewable sources and load into account. Yang et al. [12] proposed a rolling optimization planning

List of abbreviations including units and nomenclature: ε_{PV}, random component of PV real generation; $\varepsilon_{forecast\#n}$, random component of PV forecast accuracy #n; ANN, artificial neural network; BESS, battery energy storage system; E_0, nitial energy stored into the battery; E^{bat}_{min}, minimum stored energy allowed; E^{bat}_{max}, maximum stored energy allowed; O&M, operation and Management; PLD, Hourly spot-market energy price (US$/MWh); PV_{real}, photovoltaic real generation (kWh); PV_{contr}, photovoltaic contracted generation (kWh); $PV_{forecast\#n}$, predicted photovoltaic generation with forecast accuracy #n (kWh); P_{bat}, energy dispatched from battery (kWh); P_{min}, battery minimal power output (kW); P_{min}, battery maximal power output (kW); R, revenue (US$).

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The complementary nature between wind and photovoltaic generation in Brazil and the role of energy storage in utility-scale hybrid power plants

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ARTICLE INFO

Keywords:
Hybrid solar and wind
Photovoltaics
Energy Storage
Solar and wind resource complementarity

ABSTRACT

Solar and wind sources together provided more than half of the Brazilian Northeast electricity generation in 2019. This growing share of renewable energies in the Brazilian energy matrix increases the importance of portfolio optimization and the energy storage management. This paper assesses the complementary nature between wind and photovoltaic generation in the Brazilian Northeast, and how this complementarity, together with energy storage, can reduce the shortcomings that the corresponding natural resource intermittency imposes on these sources. The work consists of two main analyses: (i) analysis of the capability in supplying the Brazillian Northeast region power demand with a hybrid wind + solar + storage power plant; and (ii) contingency optimization analysis for hybrid wind + solar + storage power plants. The results show that wind and solar resources are consistently complementary in the region, with a daily Pearson's Correlation Coefficient of −0.51. Also, the load supply analysis shows that a renewable energy mix based on a 40% wind and 60% solar share would require the equivalent of only 6% of its annual generation in storage capacity. An energy curtailment analysis showed that the complementary nature of the wind and solar resources, together with energy storage, can lead to a reduction of up to 11% in transmission capacity demand.

1. Introduction

Renewable energy (RE) generation technologies accounted for 72% of the worldwide net generation capacity expansion (245 GW) in 2019, with solar and wind accounting for 90% of the 176 GW in newly added global RE generation capacity [1]. The intermittent and non-dispatchable nature of these two RE technologies can lead to variability issues in demand supply. Therefore, strategies to avoid or attenuate the effects of these resources' variability have become an important field of study. Brazil is a specific case due to its vast territory, with more than 8,500,000 km2 and latitudes ranging from 5°N to 33°S. With an installed generation capacity of over 170 GW, the Brazilian energy mix is very diverse in resources, with 62% of its energy being provided by hydroelectricity, 26% by thermoelectric plants (16% fossil fuel, 9% biomass, 1% nuclear), and around 12% by non-dispatchable RE sources (9% wind and 3% solar) [2]. Despite all the advantages provided by the major role of hydropower in the electricity mix, it also leads to a high dependency on the rainfall regime and water flow in the river basins. In recent years, river basins located in the Northeast have experienced intense water constraints, with water flow decreasing by up to 99% in some cases [3]. The impact of the drought period in the Northeast subsystem is being attenuated by the increasing penetration of RE in the region, which accounts for the highest solar and wind resource availability and installed capacity in the country [4,5]. The high availabilities of both resources create opportunities for wind + solar hybrid power plants, as shown by their geographical distribution shown in Fig. 1. Both wind and PV large-scale power plant projects are being installed in close proximity and, therefore, many projects share the same access point to the Brazilian Interconnected Transmission System (*Sistema Interligado Nacional - SIN* in Portuguese), and the high-voltage transmission lines. This increasing RE penetration and its concentration in the NE region start to demand solutions for issues such as the generation variability and curtailment losses due to transmission system congestion [6–8]. In this context, the present study aims to assess the temporal complementarity between the solar and wind resource availability and potential output generation, and how this complementarity,

Abbreviations: η_{ESS}, Energy storage system efficiency in %; ANEEL, Agência Nacional de Energia Elétrica (Brazilian Electricity Regulatory Agency); EPE, Empresa de Pesquisa Energética (Brazilian Energy Research Enterprise); GHI, Global horizontal irradiation; LOLP, Loss of Load Probability; MISO, Midcontinent Independent System Operator; N, North; NE, Northeast; ONS, Operador Nacional do Sistema (National Electricity System Operator); PCC, Pearson's Correlation Coefficient; PV, Photovoltaics; RE, Renewable Energy; S, South; SE/MW, Southeast/Midwest; SIN, Sistema Interligado Nacional (Brazilian Interconnected Electricity System

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Review

Automatic Inspection of Photovoltaic Power Plants Using Aerial Infrared Thermography: A Review

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Abstract: In recent years, aerial infrared thermography (aIRT), as a cost-efficient inspection method, has been demonstrated to be a reliable technique for failure detection in photovoltaic (PV) systems. This method aims to quickly perform a comprehensive monitoring of PV power plants, from the commissioning phase through its entire operational lifetime. This paper provides a review of reported methods in the literature for automating different tasks of the aIRT framework for PV system inspection. The related studies were reviewed for digital image processing (DIP), classification and deep learning techniques. Most of these studies were focused on autonomous fault detection and classification of PV plants using visual, IRT and aIRT images with accuracies up to 90%. On the other hand, only a few studies explored the automation of other parts of the procedure of aIRT, such as the optimal path planning, the orthomosaicking of the acquired images and the detection of soiling over the modules. Algorithms for the detection and segmentation of PV modules achieved a maximum F1 score (harmonic mean of precision and recall) of 98.4%. The accuracy, robustness and generalization of the developed algorithms are still the main issues of these studies, especially when dealing with more classes of faults and the inspection of large-scale PV plants. Therefore, the autonomous procedure and classification task must still be explored to enhance the performance and applicability of the aIRT method.

Keywords: aerial infrared thermography (aIRT); PV power plant; PV monitoring; deep learning; automatic fault detection; PV reliability

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1. Introduction

As the world experiences a continuously growing share of photovoltaics (PVs) in the energy mix, increasing the performance and reliability of PV installations is of utmost importance. In this context, infrared thermography (IRT) has become a well-established and competitive fault detection method for the condition monitoring and maintenance of PV systems [1]. It provides reliability and accuracy in the detection of typical PV module faults such as bypassed or disconnected substrings, microcracks, soldering problems, shunted cells and disconnected modules. Another feature of this technique is the possible large-scale applicability, through the combination of IRT cameras with an unmanned aerial vehicle (UAV), configured for aerial infrared thermography (aIRT) [1,2].

The first description of the potential of using aIRT in the literature was given in 2012 by Denio [3]. This was followed by the publication of the results of an experimental setup that inspected 60 different PV plants of up to 1 MWp, based on a remote-controlled drone [4]. Since then, several publications have demonstrated the technique's capability to detect failures in photovoltaic systems quickly and efficiently from the commissioning phase of the power plant through its expected 25 years of operation [5–9].

To further improve the time and cost efficiency of the method, the automation of the entire procedure of the aIRT technique has been assessed in recent years by several

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The role and benefits of residential rooftop photovoltaic prosumers in Brazil

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ABSTRACT

With the declining costs of photovoltaics (PV), a recent and widespread uptake of residential rooftop PV is underway in Brazil and many other sunbelt countries. Electricity consumers produce some or all their energy and become prosumers = producers + consumers. We present a method to evaluate the role and benefits of residential rooftop PV to prosumers and show a case-study using one of the 1250 PV-powered households in the "Celesc PV Bonus Project", promoted by the local distribution utility Celesc to demonstrate our method in Florianópolis-Brazil. The methodology was divided into five principal stages: (i) Solar resource at the site; (ii) PV system performance indicators; (iii) Consumption profiles; (iv) CO_2 emissions avoided and; (v) Comparative analysis between the individual PV rooftop case study with the average of PV households in the Florianópolis region. From the utility's perspective, the annual electricity consumption was reduced by 18% after PV integration. From the prosumer's perspective, the total annual consumption increased by 8%. However, the annual reduction in electrical utility expenses was 54%. The adoption of rooftop PV in residential households in Brazil was demonstrated to be advantageous, and payback times are still on a downward trend due to the continuing price reductions experienced by the PV technology.

1. Introduction

Technological advances and the desire for decarbonization are factors that have been transforming the energy sector worldwide, changing the traditional means of electricity generation and consumption. The residential sector contributes to a very dynamic and evolutionary scenario, due to the use of more efficient electrical appliances, the uptake of electromobility with home charging and the possibility of vehicle-to-home (V2H) and vehicle-to-grid (V2G), as well as the integration of self-generation with photovoltaic (PV) systems and batteries, which impact the generation, transmission, and distribution of electricity [1–5].

Buildings are responsible for most of the world's energy consumption [6,7]. Therefore, the concept of the Zero Energy Building (ZEB) [8–15] makes perfect sense because the reduction in the energy demand of buildings in the distribution utility grid reduces the need to build large generating plants to feed urban centers. The application of PV systems to the building envelope is an adequate technological solution to supply electricity to buildings and can occur in two different approaches: building-applied photovoltaic systems (BAPV) and building-integrated photovoltaic systems (BIPV). BAPV is a term used when the installation of PV modules is done on existing roofs, that is, their application is made on a previously designed surface that typically had not been designed for a PV system; therefore, they do not necessarily follow the original characteristics of the architecture or construction. In BIPV systems, photovoltaic modules are inserted in the architecture from the project design stage and aim to integrate as much as possible the solar PV generation with the building architecture, maintaining the aesthetics and function through the use of PV technologies that can replace some constructive materials such as walls and fences, roofs, shading devices or facades [7,16–23].

The average levels of Global Horizontal Solar Irradiation (GHI) recorded in Brazil are among the best in the world, reaching in excess of 2230 kWh/m^2.year [24]. The lowest annual solar irradiation averages in the Brazilian territory are recorded in the Southern region of the country, as shown in Fig. 1.

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CAPABILITY STATEMENT – CUTTING EDGE APPLIED R&D ON UTILITY-SCALE PV POWER PLANTS

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journal homepage: www.elsevier.com/locate/solener

Extreme solar overirradiance events: Occurrence and impacts on utility-scale photovoltaic power plants in Brazil

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ARTICLE INFO

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Overirradiance
Cloud enhancement
Irradiation
PV system performance
Utility-scale PV power plants

ABSTRACT

In contrast to the decades-long accumulated experience of photovoltaic (PV) installations in more temperate climates, the effects of some extreme operating temperatures and extreme solar irradiance levels start to become more noticeable with the uptake of large-scale PV in the sunbelt regions of the world. One such effect is caused by extreme solar overirradiance events, which up to now have been reported in the literature much more for their scientific interest than as a potential problem affecting the operational performance of PV power plants. Solar overirradiance events with a time span of tens of seconds or minutes are associated with the high operating temperatures prevailing in the field at many sites where utility-scale PV power plants start to become widespread, deleterious effects can be observed, which will negatively impact the performance of these generators. Using irradiance data from seven solar measuring stations deployed over distinct regions in Brazil, many of which are hosting megawatt-scale PV power plants, this paper reports on several extreme solar overirradiance events, with measured values above 1367 W/m² up to 1845 W/m², lasting from many seconds to a few minutes. Analysis of impacts and consequences from these events on the operational performance of PV generators are addressed, mainly focused on combiner box fuses, inverter overload losses, and inverter maximum power point tracker.

1. Introduction

Brazil has an excellent solar energy resource availability (Pereira et al., 2017). With the declining costs of photovoltaic equipment, solar photovoltaic (PV) generation prices are levelling with wind, hydro and other renewable energy sources in Brazil. Consequently, the Brazilian government and electricity companies have started to evaluate and consider utility-scale PV power plants as a large contributor to the electricity mix. Grid-connected photovoltaic systems exhibit a close to linear response to solar irradiance (G), which plays the most important role in solar power generation. PV modules electrical data are rated at Standard Test Conditions (STC, 25 °C cell temperature, 1000 W/m² in-plane irradiance, and AM = 1.5 spectral distribution of incident sunlight). For laboratory rating purposes, an irradiance value of 1000 W/m² (normally emitted by a flash solar simulator) is applied perpendicularly to a PV module surface to determine its nominal maximum power value (STC-rated peak power, Wp) and other electrical data. However, in the field, irradiance values above 1000 W/m² are expected, even at higher latitudes, but normally not considered as frequent or lasting long enough in order to play a significant role on PV module and system performance.

The normal extraterrestrial solar irradiance is the value incident at the top of the atmosphere, on a plane surface placed perpendicular to the solar rays. At the average Sun-Earth distance, the normal extraterrestrial irradiance is called solar constant, G_0. Although not strictly constant, in this paper the value of 1367 W/m² was adopted for G_0, which is the amount of solar power flux (irradiance, in W/m²) that passes through the mean Earth orbit (Piacentini et al., 2003; Piacentini et al., 2011; Yordanov and Saetre, 2014).

Overirradiance is a phenomenon characterised by short-term enhancement of the solar irradiance measured at the Earth's surface which occurs under broken cloud fields, when a visible cloud brightening effect (commonly called cloud-enhancement- or cloud-edge-effect) takes place (Pfister et al., 2003). Overirradiance events are observed for all wavelengths in global horizontal and global tilted irradiance (Iqbal, 1983; Träger, 2012).

An overirradiance event is identified when the measured irradiance is higher than horizontal extraterrestrial irradiance (ETH) values (Kt > 1) where Kt = GHI/ETH (Gueymard, 2017a). Depending on the time of day overirradiance values can be much lower than the STC irradiance (1000 W/m²) and present no relevance or potential problems affecting PV power plants operational performance. For quantifying the

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Solar Over-Irradiance Events: Preliminary Results from a Global Study

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***Abstract*— This paper presents a methodology and preliminary results from a global study of solar over-irradiance events, which happen more often than previously believed and can harm utility-scale PV operations by interfering with a site's power electronics. Data from five test sites in Florianópolis and Brotas de Macaúbas in Brazil, Bernburg in Germany, Albuquerque, in the USA and Loughborough, in the United Kingdom are presented and analyzed.**

***Keywords*— Over-irradiance; Irradiance enhancement; Solar irradiation; PV system performance.**

I. Introduction

Over-irradiance, defined as a magnification of irradiance reaching the earth's surface, occurs all over the world and has been reported in the literature for many decades ([1] and references therein), but more as a scientific curiosity than as an issue of economic or technical importance for photovoltaic (PV) systems. A recent study, however, [1] showed that over-irradiance events impact the performance of utility-scale PV power plants, especially when the events last longer than 1 min and occur when ambient temperatures exceed 30°C. Under those conditions, a sudden burst of over-irradiance can blow string fuses and overload inverters, leading to energy losses. In other words, it is the extended high magnitude events that are most concerning to plant operations.

Yet the occurrence of over-irradiance events and their effects on PV power plants are not well quantified, largely because over-irradiance is so brief in duration (generally less than 5 seconds per episode) and therefore requires high-frequency (~1 s) irradiance data to be detected. In addition, the impact of over-irradiance on a PV system's power electronics depends on location and climate, which in turn determine the fuse operating temperature, and on the PV system overall design employed.

This study, aims to identify solar over-irradiance events, their prevalence and duration at PV CAMPER's ("PhotoVoltaic Collaborative to Advance Multiclimate Energy Research") [2] member sites and evaluate their impact on utility-scale PV performance across different sites/climates. The purpose of this paper is to present the methodology implemented in the study and its preliminary results for five different locations: Florianópolis and Brotas de Macaúbas in Brazil, Bernburg in Germany, Albuquerque in the USA, and Loughborough in the United Kingdom.

II. Background

Worldwide measurements to further PV research in multiple areas, including over-irradiance, that affect the performance of power plants, are badly needed. To address that need and to ensure that data generated globally is similar in quality, multiple research organizations decided to form PV CAMPER. This collaborative represents a global research platform with common infrastructure and protocols to address persistent PV performance challenges (uncertainty drivers, degradation rates, soiling losses, component failures), increase the accuracy of performance models, and to generate a set of best practices for data monitoring and collection [2][3]. To that end, PV CAMPER membership requires participating institutions to have well-maintained field sites with comparable meteorological and irradiance instrumentation and to commit to a common set of data-quality standards. PV CAMPER's 12 founding members collectively represent a total of 15 field sites spread across the world's main climatic zones (see Fig. 1 and [2]). To support the work being undertaken and benefit the PV industry, PV CAMPER has established a global data repository for meteorological and performance data that is accessible to its members [4].

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Performance assessment issues in utility-scale photovoltaics in warm and sunny climates★

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Abstract. With the declining costs of photovoltaics (PV), and the excellent solar energy resource availability in the country, the Brazilian government and the electricity sector have started to evaluate and consider PV as a serious potential contributor to the National electricity mix. Since the late 1990s, Brazilian electrical utilities are required by the National Electrical Energy Regulatory Agency ANEEL to invest 1% of their operational income on R&D. In 2011, ANEEL issued an R&D call dedicated to utility-scale PV. The solar energy research group at Universidade Federal de Santa Catarina (www.fotovoltaica.ufsc.br) has been actively investigating and promoting PV in Brazil, operates since 1997 the first grid-connected, thin-film PV generator in the country. Under the ANEEL R&D call, a 4-year, US$ 20 million project was started in 2012. The project aims at assessing the performance of seven different PV technologies at eight different Evaluation Sites (ES) in Brazil, and also to design, procure, install and monitor the performance of a utility-scale 3 MWp R&D PV power plant, which is located at one of these eight ES. The 3 MWp PV power plant and all the eight ES are fully monitored, with all electrical and environmental parameters measured at 1-s intervals. PV technologies include thin-film amorphous silicon (a-Si), microcrystalline silicon (μc-Si), cadmium telluride (CdTe), copper indium gallium diselenide, mono- and multi-crystalline silicon (c-Si and m-Si), all at fixed tilt, as well as double-axis tracking, concentrated PV using triple-junction InGap/GaAs/Ge at 820 suns concentration. All ES are identical, except for the fixed PV arrays tilt angle, which is equal to the latitude at each site. The 3 MWp R&D PV power plant is co-located at one of the ES sites. Thin-film PV technologies with a low temperature coefficient of power presented superior output performance, and cloud-edge and cloud-enhancement effects of solar irradiance resulted in operational issues that were not previously described in the literature. Inverter Loading Ratios commonly described in the literature (for less sunny sites) led to considerable annual energy losses.

1 Introduction

The widespread utilisation of solar photovoltaics (PV) in utility-scale, large-area power plants in warm and sunny climates like Australia and Brazil is fairly recent. The influence of high operating temperatures, extreme over-irradiance events due to cloud-edge and cloud-enhancement effects [1–8], and soiling [9–12] on the performance of PV power plants is much more extreme in these countries than in the more temperate climates where most of the ~300 GW of PV operate worldwide [13–20]. The negative temperature coefficient of power of the crystalline silicon and the copper indium gallium diselenide (CIGS) thin-film PV technologies are both in the order of −0.4 to −0.5%/°C, while for the thin-film amorphous silicon and cadmium telluride CdTe PV technologies it is around −0.2%/°C. High ambient temperatures, associated with high irradiance levels, can lead to PV device operating temperatures in excess of 80 °C if wind speeds are low, resulting in considerable output losses for all PV technologies. At sites with disperse cloud coverage, cloud-edge and cloud-enhancement effects can lead to irradiance levels in excess of 1800 W/m^2. These two effects combined can lead to a cascade of string-box fuse burnings in large-area PV fields if fuses are not properly specified. On the other hand, PV module manufacturer maximum series fuse ratings, designed originally for more temperate climates, are somewhat narrow, and the properly specified fuse for a PV array string box under the operating conditions described above might exceed the particular PV module maximum series fuse rating, voiding PV module warranty. Soiling is also an issue that will affect more the output of large-scale, ground-mounted PV power plants in warm and sunny

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Optimization of inverter loading ratio for grid connected photovoltaic systems

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ABSTRACT

This study is aimed at performing and analyzing the inverter sizing optimization process for large-scale grid-connected solar photovoltaics (PV). The local solar resource was evaluated and compared to the available satellite data. Analyses of the solar irradiance distribution and its potential effects on inverter sizing were performed. The performance of five different, commercially-available PV module technologies was also evaluated by means of remote data analysis of irradiation and temperature, as well as electrical parameters. This was performed using the metrics of energy yield and performance ratio (PR) for PV systems. A methodology was developed for estimating the optimal inverter sizing in the region considering overload losses and economic aspects, aiming at the optimization and cost reduction of PV-generated electricity. Considering the five technologies, the mean yield was 150 kWh/kWp on a monthly basis. The annual PR ranged from 77% to 85% depending on technology. The local solar resource, measured during three years, was compared to five distinct satellite-derived solar databases. Cloud enhancement and cloud edge effects were observed through the monthly solar irradiation distribution over the three years of measurements. Around 28% of the incident annual irradiation was at irradiance levels at or above 1000 W/m^2. The methodology developed for the optimal inverter loading ratio (ILR) was applied over one full year of solar generation data for the five technologies. It was observed that for inverter loading ratios commonly used on utility-scale PV power plants (around 120%), the overload losses varied from 0.3% to 2.4%, depending on technology. The optimal ILR for the more traditional crystalline Si PV technology was estimated to be 126%.

1. Introduction

Future projections indicate that the electricity consumption in Brazil will reach 690 TWh/year by 2024 (MME, 2015a,b). That is an annual growth of 3.9%, when compared to the current 524 TWh/year (2017). The country has great potential for the use of renewable energy such as hydro, wind, biomass and solar and can therefore diversify its energy matrix and cope with the increasing demand in a sustainable manner. In recent years, Brazil has finally seen the rise of solar photovoltaics (PV) both in large-scale power plants and small distributed generation (DG) PV systems.

For distributed solar, the National Regulator Agency (ANEEL) established Resolution no. 482/2012, which implemented net-metering for systems up to 1 MW (later increased to 5 MW), for both households, public buildings and companies. This, together with ever increasing conventional electricity tariffs, has resulted in the current exponential growth the uptake of this technology is experiencing in the country. ANEEL projects growth to close to one million systems (over 3 GWp) by 2024 (ANEEL, 2017).

For centralized large scale solar, the government promoted so far six energy auctions between 2013 and 2018. Although solar photovoltaic was only successful starting in 2014, since then, 143 projects were contracted, totaling 5030.95 MWp (4033.44 MW) (MME, 2014, 2015a,b, 2016; EPE, 2017, 2018; CCEE, 2017). In Brazil, the installed power is defined as being the smaller value between DC power (PV modules) and AC power (inverters), the smaller being usually the AC power. The Inverter Loading Ratio (ILR – DC to AC power ratio) of all 143 projects combined is approximately 125%.

The Brazilian northeast region has an enormous potential in terms of solar resource and consequently houses the great majority of the projects contracted in these auctions. It is important to carry out studies aimed at optimizing the PV energy generation in the local conditions. Studies that are based on the irradiance profile, inverter loading ratio and performance of different photovoltaic technologies can have a substantial impact on the total costs of the energy generated. In addition, many of the PV systems used as a case study for inverter loading

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Evaluating the performance of radiometers for solar overirradiance events

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ABSTRACT

This paper describes a methodology used to evaluate pyranometers and reference cell performance in relation to solar overirradiance (OIR) events. By definition, these events are characterized when global horizontal irradiance (GHI) exceeds the extraterrestrial horizontal irradiance (ETH) due to cloud enhancement (CE) effects (e.g. scattering, reflection, cloud lense augmentation). Evaluation metrics are proposed to assess relevant features of the events such as uncertainty, event identification, and response time. The metrics were validated with high standard radiometers deployed at the Solar Energy Research Laboratory Fotovoltaica/UFSC in Florianópolis, Brazil. The results were checked against solar radiometers' specifications, and sensors were analyzed according to their performances. An ISO outdoor calibration, as well as a system uncertainty analysis and data response time evaluation, were performed, to assure results reliability. In addition, two extreme overirradiance (EOIR) events were evaluated separately, and seasonal occurrence of the energy fraction of overirradiance events was assessed and discussed.

1. Introduction

Photovoltaic (PV) is one of the fastest-growing segments of the energy generation market. Utility-scale PV power plants and distributed integrated PV systems have been installed worldwide. In order to keep track of important aspects such as operation, maintenance, performance, resource assessment for PV system design (e.g. inverter load ratios), forecasting, etc; fast and accurate radiometers are used. The solar resource is intensively influenced by cloud cover and weather conditions, in most regions. The effect of clouds on surface irradiance is significant, causing steep ramps, culminating in highly variable fast and intense irradiance events, which can have a considerable impact on PV power plant output (Denholm and Margolis, 2007a, 2007b). Overirradiance (OIR) events have been reported in the literature with renewed interest, especially in sunbelt countries, which are more prone to particular cloud pattern distribution (Almeida et al., 2014; Do Nascimento et al., 2019, 2020, Gueymard, 2017a,b; Inman et al., 2016; Järvelä et al., 2020; Lappalainen and Kleissl, 2020; Rüther et al., 2017; Vamvakas et al., 2020; Yordanov et al., 2015; Norris, 1968). OIR has also been reported to cause operational issues, such as inverter overload, fuses burning associated with high temperatures, and cascade shutdown of the protection circuits in large PV plants (Burger and Rüther, 2006; Chen et al., 2013; Luoma et al., 2012). As a matter of fact, this phenomenon does not have a formal nomenclature adopted in the literature, being defined by overirradiance (OIR), over-irradiance, cloud enhancement (CE), cloud edge, or cloud lensing (Balfour et al., 2011; Braga et al., 2020; do Nascimento et al., 2019; Gueymard, 2017a; Wirth et al., 2015). In the present work, overirradiance (OIR) will be adopted.

Overirradiance occurs due to interactions of the solar path with atmospheric molecules and particles towards the earth's surface. On its way, the radiation can be absorbed, scattered, or reflected. Rayleigh (RS), Mie (MS), and Non-selective scatterings (NSS) are dominant and cause distinct observable color effects (Lillesand and Kiefer, 1994; Mantelli Neto et al., 2020). RS is responsible for red, blue, and yellow sky colors, while MS is responsible for haze. On clear skies, RS and MS are the dominant events and, in no circumstances, can cause OIR. Clouds cause NSS on equally likely all visible wavelengths resulting in white color. It is clear that OIR is caused by the presence of clouds, but not in all circumstances. Clouds mostly reduce the amount of irradiation reaching the surface, however, they can occasionally enhance it. That is the reason the authors believe that NSS is not the sole reason for OIR, especially with dense clouds and dark bases indicating energy

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O&M | The use of unmanned aerial vehicles in solar operations and maintenance can reduce costs and save hours of painstaking labour, but only if applied correctly. Aline Kirsten Vidal de Oliveira, Mohammadreza Aghae and Ricardo Rüther explore the optimal use of aerial inspections and emerging methods for analysing the data they gather to identify faults

As photovoltaic (PV) installations increase in number and scale worldwide, the need for reliability and optimum performance of PV power plants grows as well. Thus, it is essential to develop fast and efficient inspection techniques, to perform operation and maintenance (O&M) measures cost-effectively.

With the advent of commercially available unnamed aerial vehicles (UAVs), aerial inspections were developed to be one of the novel methods for O&M which seems to be a promising approach to this challenge. This article aims to discuss the advantages and challenges related to aerial inspections in large-scale PV power plants, discussing the association of UAVs with consolidated inspection methods such as visual inspection, infrared thermography (IRT) and electroluminescence (EL).

Aerial inspections

UAVs are typically small-scale aircrafts capable of remote or autonomous operation. They were originally designed for military purposes. However, recent advances and cost reductions in the field of UAV have made such technology applicable for civil operations such as disaster relief, energy and power line inspections, and environmental, forest and mine monitoring, among others [1]. The technology has become increasingly popular, especially in the energy and agriculture sectors.

The use of UAVs to inspect large PV plants has grown significantly over the years, thanks to their superiority in field coverage, reliable imaging, quick detection, high durability, lightweight, low cost and high robustness to operate in hostile environments. They are used with RGB cameras or with cameras for infrared thermography (IRT) or electroluminescence (EL).

Drone-enabled inspections of PV power plants are increasingly popular in solar O&M

The widespread adoption of such devices also increased the availability of controlling and route planning software. The prior path definition of the flights enables a more stable, safe and effective inspection, mostly when precise GPS data of the site is available. Nonetheless, it does not detract from having a trained workforce for conducting the flight. The routes can vary in terms of height, direction and velocity, which depends on the quality of the UAV and the camera, the shape of the power plant, wind speeds during flight, and the goal of the inspection. The direction of the route, for example, can be parallel to the module rows or orthogonal to them, as shown in Figure 1. None of the two methods

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Performance assessment of solar photovoltaic technologies under different climatic conditions in Brazil

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A B S T R A C T

Utility-scale photovoltaic (PV) generation is being ramped-up in Brazil in recent years, as a result of intense price reductions. Extreme operating temperatures, high humidity levels, and a blue-biased distribution of irradiance in comparison with the standard ASTM G-173 spectrum, lead to contrasting operational outputs of the various commercially-available PV technologies. The performance assessment of six different PV technologies installed at eight different climatic regions in Brazil is presented. This R&D project evaluates eight identical, 54 kWp Evaluation Sites (ESs), all with the following PV technologies: amorphous-silicon (a-Si), microcrystalline-silicon (μc-Si), cadmium-telluride (CdTe), copper-indium-gallium-diselenide (CIGS), mono- and multi-crystalline silicon (c-Si and m-Si). All installations operate at a fixed-tilt equal to the corresponding local latitude. Electrical and environmental parameters at all sites are measured continuously at 1-s intervals. Results show a detailed energy loss analysis for all technologies. Thin-film PV modules with a low temperature-coefficient of power presented superior performance. Crystalline silicon modules revealed intense degradation in areas with high relative humidity and temperature. Cloud-edge and cloud-enhancement effects of solar irradiance resulted in irradiance peaks of 1823 W/m^2, with long overirradiance events which lasted many minutes over 1600 W/m^2, resulting in frequent blowing of string fuses when manufacturers maximum fuse ratings were observed.

1. Introduction

In recent years, due to the declining costs of photovoltaics (PV), and the excellent solar energy resource availability in the country, the Brazilian government and the electricity sector have started to evaluate and consider PV as a serious potential contributor to the national electricity mix. Utility-scale PV is gaining momentum in Brazil, and after the successful introduction of large-scale wind generation in the late 1990's, solar generation is now enjoying an exponential growth in the country. Since the late 1990's, Brazilian electrical utilities are required by the National Electrical Energy Regulatory Agency (ANEEL) to invest 1% of their operational income on research and development (R&D) projects. In 2011, ANEEL issued a R&D project call dedicated to utility-scale PV. The solar energy research group at the Universidade Federal de Santa Catarina/UFSC (www.fotovoltaica.ufsc.br) has been actively investigating and promoting PV in Brazil, and operates since 1997 the first grid-connected, thin-film PV generator in the country [1–3].

This paper presents the main results of this R&D project with the PV assessment of six, fixed-tilt, flat-plate PV technologies installed at eight different sites with distinct Brazilian climatic conditions. The PV performance at each site is evaluated through the calculation of the performance ratios (PRs) for measured data for each PV technology, and a comprehensive analysis of these results is given.

A detailed energy loss analysis carried out with the use of computational simulation is also presented for two of the evaluation sites (ESs). The results are compared with those obtained from measured data of a full year of operation of the PV systems. The differences observed between simulated and measured losses along with simulation uncertainties are discussed. The results also reveal some of the peculiarities observed during the continuous and high-temporal-resolution monitoring of PV generators at all these warm and sunny sites.

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The influence of the solar radiation database and the photovoltaic simulator on the sizing and economics of photovoltaic-diesel generators

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A B S T R A C T

This study evaluated the outcome differences when adopting five different solar irradiation databases on the sizing of hybrid solar photovoltaic-diesel generators designed to supply electricity to isolated minigrids. To do this, the two most widely adopted photovoltaic (PV) simulation packages in the market, namely PVsyst® and HOMER Energy® were used. The different origins, data timespan, space and time resolution, of the five most relevant solar irradiation databases available for the region were compared. A case study was presented to illustrate the influences of the solar irradiation database and the solar simulation tool on the resulting PV generator. Furthermore, the hourly behavior of the energy supply to an existing load in a minigrid in the Brazilian Amazon was evaluated, together with the savings in diesel obtained with the resulting PV generator. Evaluating the five options of solar radiation databases, for the same PV plant configuration, variations of up to 19.7% were found in the expectation of PV generation. When the simulation software package was varied, the combined effect (radiation database X PV system sizing tool) showed differences of up to 20.6%. This demonstrates that despite having different algorithms, computational tools have a small influence (less than 1%) on results. These combined differences, taking into account the load curve behavior and the total diesel generation capacity installed at the site, resulted in over 100% differences in the optimum PV generator size in the case study. The total savings in diesel fuel, over a 15-years period, ranged from $ 6.5 million to over $ 16 million (> 2.5 times) for the smallest PV system. This demonstrates the importance of the correct choice of database. These evaluations can be extended to minigrids of any size elsewhere. The novelty and originality of this study is to demonstrate and quantify for the first time the influence of the solar radiation database and the PV simulator package on the sizing of PV-diesel generators. The consequences of this study are not only of scientific and academic importance, but of economic and commercial interest as well.

1. Introduction

Electricity supply in Brazil is carried out through one of the largest and most complex transmission and distribution systems in the world, the so-called SIN (the Brazilian Interconnected System, or *Sistema Interligado Nacional* in Portuguese). The SIN spans over 181 thousand kilometers, and supplies electricity to around 99% of Brazilian consumers in the 8.5 million km^2 National Territory [1]. The energy generation mix is comprised predominantly by hydroelectricity (61%), followed by wind (8.7%), biomass (8.5%), natural gas (7.8%), oil (5.1%), coal (1.9%), solar (3.1%), nuclear (1.1%), and imports (2.6%) [2]. The SISOL (the Brazilian Isolated Electricity System, or *Sistema Isolado* in Portuguese) on the other hand, currently supplies about 3 TWh/year of electricity in minigrids (which represents less than 1% of the 482 TWh consumed in the country in 2019) to 235 small towns and villages, in which less than 1% of the remaining Brazilian population lives [3]. Most of these minigrids are located in the Amazon region in the states of Amazonas (AM), Pará (PA), Rondônia (RO), Roraima (RR), Acre (AC), and Amapá (AP), covering around 42% of the National Territory. Energy supply to the region plays a strategic development and national sovereignty role [4]. Fig. 1 shows the evolution of SISOL's electricity consumption from 2004 to 2019. The dotted line represents the fraction of SISOL with respect to the total electricity consumption in the country (SIN + SISOL) over the same period. The decrease in the relative fraction of energy consumed in the SISOL over the years is due to the Ministry of Mines and Energy's (MME) efforts in interconnecting a large fraction of these minigrids to the SIN, especially in the North and Northeast of the country. Between 2009 and 2013, the Amazon capitals of Rio Branco-AC, Porto Velho-RO and Macapá-AP were interconnected, and between 2013 and 2014 a 34.8% reduction in the

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Towards the maximum efficiency design of a perovskite solar cell by material properties tuning: A multidimensional approach

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Cell designs

ABSTRACT

To obtain significant increases in the Power Conversion Efficiency (PCE) of solar cells, we argue that the substitution of the state-of-the-art one- and two-dimensional cell optimizations, by the simultaneous improvement of multiple material properties is of substantial advantage. In this context, researchers should know, which combined material properties and cell design parameters result in the highest efficiency increase. For the same objective, it is also of importance to know, which ideal relationships in-between these variables have to be adjusted. Such knowledge becomes available by simulations and numerical optimizations, which we present for a Perovskite Solar Cell (PSC) in a hypercube space of model variables. We prove that its PCE increases principally because of the nonlinearities inherent to its mathematical model, and therefore, we elucidate the importance of the multidimensional variable improvements in the PSC's optimization. We increased the PCE to a value of at least 27.6% by simultaneous improvements of the cell's material properties, and light trapping, for a large range of absorber layer thicknesses, from t_0 = 160 to 400 nm. The lower thickness results in a significant reduction of the device's Pb content.

1. Introduction

Early research in hybrid solar cells (Huang and Huang, 2014; O'Regan and Grätzel, 1991; Wong et al., 2007) led to the concept of the so-known PSC (Kojima et al., 2009), a hybrid thin-film cell, which absorber layer presents an organic-inorganic compound of semiconductor materials. In searching for new materials and properties of this device, more recent advances provided the steepest PCE increase in comparison with all other types of single-junction solar cells, reaching the state-of-the-art efficiency of 24.2% for a manufactured prototype (NREL, 2019). Several authors attempted to reduce the toxicity inherent to the heavy-metal Pb, which is a constituent of the absorber layer of high-efficiency PSCs. Such methods consider the complete (Devi and Mehra, 2019; Dixit et al., 2019), or partial substitution of this element (Liu et al., 2018). However, they result in much lower efficiencies, if compared with the state-of-the-art PCE. Our main objective is to provide more knowledge and insights about the optimization process of perovskite solar cells and propose high-efficiency designs for future PSC developments. To access this knowledge, and the design concepts, we recommend a multidimensional numerical optimization of the device's drift-diffusion model. Our design concepts present a significant PCE increase, if compared with state-of-the-art simulated and manufactured PSCs. Additionally, these concepts show a noteworthy decrease in the cell's Pb content.

In Section 2, we detail the state-of-the-art of the used methods and materials, and in Section 3, we describe our method in a general form and highlight its importance and advantage. Sections 3.1 and 3.2, define the mathematical concept and the setup conditions of our optimizations. Section 4 presents several high-efficiency cell designs, as obtained with our optimizations. Section 5 leads to an in-depth understanding of the PSC and its optimization, which we resumed in Section 6.

2. Optimization of perovskite solar cells

State-of-the-art manufacturing methods consider the PSC's

Abbreviations: FDTD, finite difference time domain modelling; IPM, interior point search method; LSM, line search method; MPP, maximal power point; NP, nonlinear programming; OTM, optical transfer matrix method; PCE, power conversion efficiency; PSC, perovskite solar cell; SSE, solvent-solvent extraction method

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Spectral modeling and spectral impacts on the performance of mc-Si and new generation CdTe photovoltaics in warm and sunny climates

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ABSTRACT

This paper presents an analysis of spectral impacts on mc-Si and new generation CdTe in two distinct regions of Brazil: Florianópolis-SC (27°S, 48°W) in the South, and Assu-RN (5°S, 37°W) in the Northeast. As utility-scale PV power plants are progressively being deployed in the Brazilian Northeast, the need for evaluation of the spectral effects of local blue-biased spectra on the energy yield of different PV technologies arises, as well as the need for spectral correction of field peak-power measurements done during commissioning and system performance tests. Considering the high cost of adequate spectral measurement equipment, this paper proposes a new approach for the estimation of spectral impacts without the need for *in loco* measurements. The proposed methodology consists of the use of satellite data acquired from NASA's Giovanni platform as inputs for the SMARTS 2.9.5 spectra model. Results for measured spectra showed that, for both locations, new generation CdTe (i.e. First Solar Series 4 and 6) has significant spectral gains: up to 10% for Assu-RN (Northeastern Brazil) and 2% for Florianópolis-SC (Southern Brazil). A seasonal variation could also be detected for the Florianópolis site, with lower spectral gains for CdTe - and higher for mc-Si - close to the Southern Hemisphere's winter solstice, due to higher air mass values and lower precipitable water content of the atmosphere. The proposed method using Giovanni data and SMARTS spectra modeling produced very similar spectra to those measured for clear days in the field at both sites, yielding good results for the calculation of spectral factors for both mc-Si and CdTe. For days with a higher diffuse fraction the results were not as satisfactory, as expected. The proposed method was also applied to instantaneous measurements for three different times (and AM values) of the day for Florianópolis: 9:00, 12:00 and 15:00, yielding satisfactory results for IV curve spectral correction.

1. Introduction

Unforeseen and impressive photovoltaic (PV) module price reductions over the last 10 years (Kavlak et al., 2018) have led to massive falling prices - and rising capacity factors and performance ratios - of utility-scale PV power plants, especially in warm and sunny climates all over the world (Bolinger et al., 2015; Parkinson, 2017, 2016; Reich et al., 2012). Cheaper PV modules gave rise to a noticeable increase on inverter loading ratios (Burger and Rüther, 2006) for ground-mounted PV plants in recent years, adding more DC (PV) power to the same AC power converter (Bolinger et al., 2015; Deschamps and Rüther, 2019). Most of these large-scale PV projects aim at selling PV electricity under long-term contracts, and close to the $ 25/MWh mark or less. While the traditional silicon technologies (c-Si, both mono- and multi-crystalline) dominate the scene, with some 97% of the world market in 2018 (Mints, 2018), high-efficiency (18% in current production and prospects of 22% demonstrated efficiencies (Bosio et al., 2018; NREL, 2018) and large-area (2.5 m^2) new generation thin-film cadmium-telluride (CdTe) PV modules have recently been introduced in the market (First Solar, 2018a, 2018b; Strevel, 2017). These improved CdTe modules present some interesting features for utility-scale PV power plants in the same warm and sunny climates where record-low prices for solar electricity are being promised. While for mc-Si PV spectral effects do not play a significant role, the narrower spectral response of CdTe results in different behaviors depending on the spectral content of sunlight at a particular site (Tsuji et al., 2018). The lower temperature coefficient on power, and the blue-shifted spectral response when compared to mc-Si, render thin-film CdTe, and the no longer commercially-available amorphous silicon PV technologies, good performers in the warm, sunny, humid and bluer skies predominant in sunbelt regions of the world (Dash et al., 2017; Munshi et al., 2018; Nann and Emery, 1992; Rüther et al., 2002; Rüther and Livingstone, 1994).

After irradiance, temperature and soiling, the spectral content of sunlight is one of the predominant variables affecting the performance

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OFF-GRID HYBRID PROJECTS: FORTRESS SANTO ANTÔNIO DE RATONES

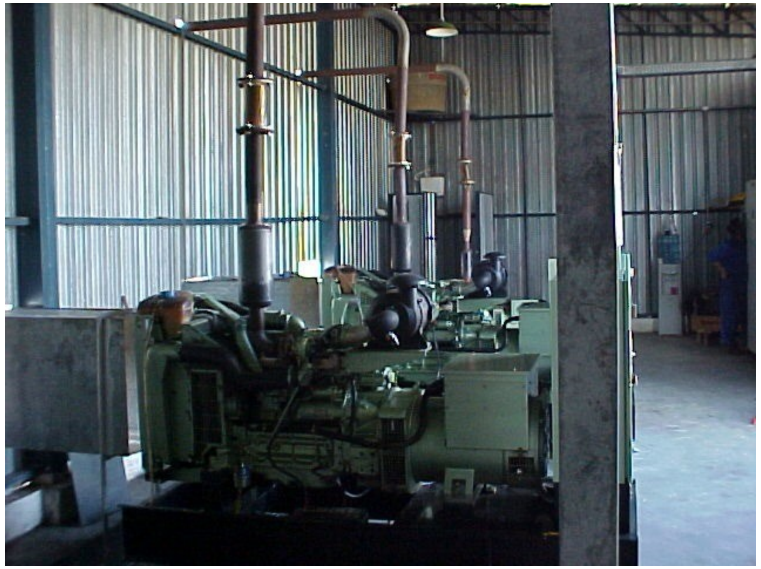
2000

PV+ Lead-Acid battery replacing diesel generator

PV: 4,7 kWp
Lead-Acid Battery: 32x150 Ah

OFF-GRID HYBRID PROJECTS: ARARAS VILAGE

2001



Hybrid PV+Diesel

PV: 20,5 kWp

ADDING PV-GENERATORS WITHOUT STORAGE TO MEDIUM SIZE STAND ALONE DIESEL GENERATOR SETS TO SUPPORT RURAL ELECTRIFICATION IN BRAZIL

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Abstract Village electrification in the power range below 100 kW in the Brazilian Amazon is actually based on Diesel generator sets supplying energy to remote local mini- and micro-grids. Some hundred of these systems are in operation. In order to analyse options for the reduction of the respective fuel consumption and thus the associated costs, we are studying the introduction of PV-generation in systems in the power range above 10 kW. More specifically, we assess technical aspects and limitations of adding PV generators without storage to the systems, taking into account the particular load characteristics and meteorological conditions in the region. We present considerations and simulations to discuss the sizing of PV arrays with respect to the fuel savings that can be gained per installed PV capacity. As validation of these calculations, the performance of a pilot hybrid Diesel / PV system without storage that is in operation in the Amazon state of Rondonia is analyzed. Based on the figures for the specific fuel savings established, we present options to turn the high overall potential for this type of PV application economically feasible for the electricity suppliers, and thus increase the PV market in Brazil.

OFF-GRID HYBRID PROJECTS: XAPURI PILOT PROJECT

2001

Development of sustainable models of rural electrification with renewable energy (103 Sytems)

The pilot project Xapuri-AC was a project promoted by Eletrobras in the scope of the technical cooperation "Renewable Energies for Rural Electrification" with GIZ (GTZ at the time). The project had as action lines: the development of sustainable models of rural electrification with renewable energy; the elaboration of proposals for public policies and regulations for the use of renewable energy; and the training of the executing agents to expand and disseminate the use of renewable energy in their concession areas.

OFF-GRID HYBRID PROJECTS: SOLAR PV APPLIED TO TRANSPORTATION AND PRODUCTIVE ACTIVITIES IN THE AMAZON

2015

Electrical engine: 2x9,5HP
PV: 4,4 kWp
Battery: 46x66 Ah

Passenger capacity: 20

OFF-GRID HYBRID PROJECTS: FIRST LIFE (100KWH) AND SECOND LIFE BATTERY (100KWH)

2022

PCS
100 kW

- First Life
  136 kWh
  - Rack 1
    68 kWh
  - Rack 2
    68 kWh
- Second Life
  105 kWh
  - Rack 3
    52,5 kWh
    105 modules
  - Rack 4
    52,5 kWh
    105 modules

fotovoltaicaufsc

OFF-GRID HYBRID PROJECTS SUNNY ISLAND + B-BOX

2022

OFF-GRID HYBRID PROJECTS: MAIS LUZ PARA A AMAZÔNIA (MORE LIGHT TO THE AMAZON)

2022

PV: 1,1kWp

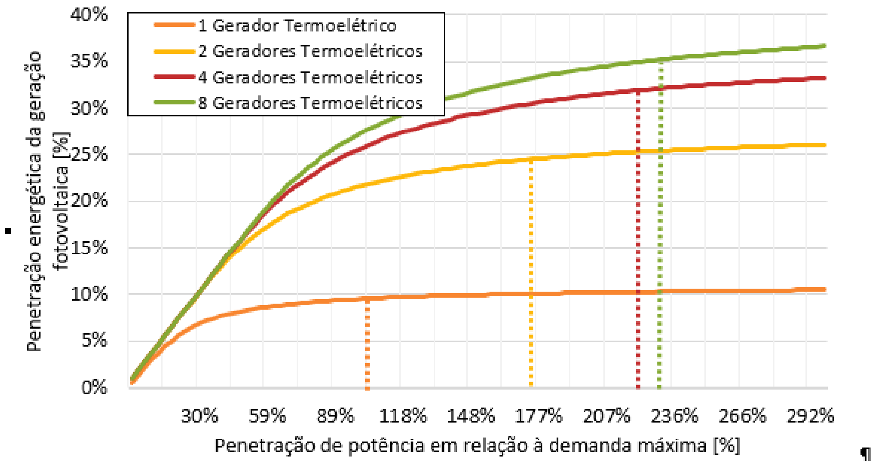
3 types of storage

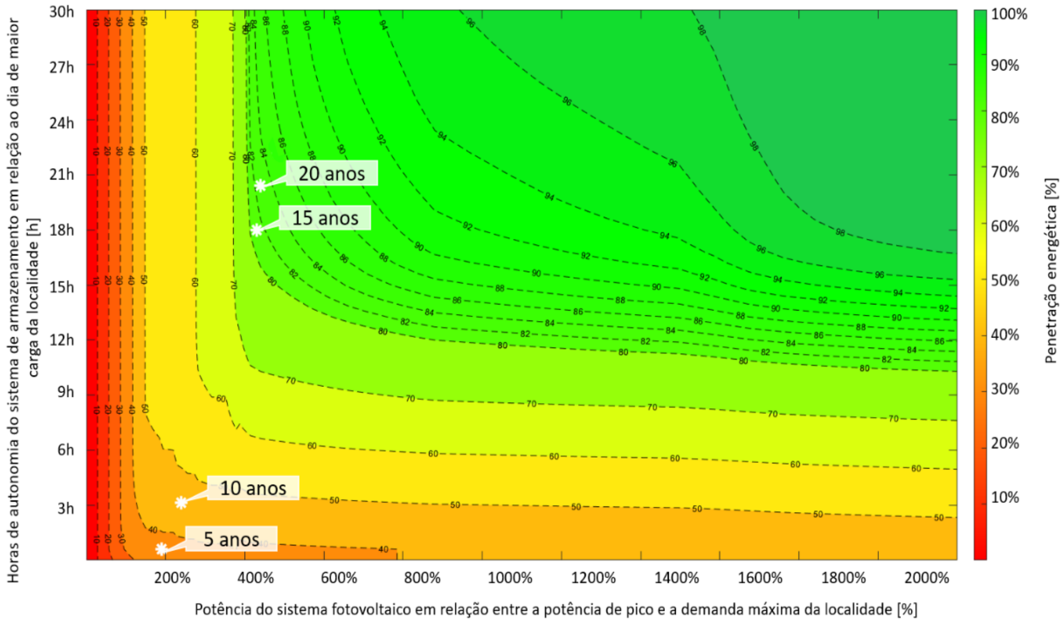
- Lead-Acid
- Lithium
- Lithium second-life

OFF-GRID HYBRID PROJECTS: CONSULTING FOR IDENTIFICATION OF TECHNICAL AND ECONOMIC MODELS OF RENEWABLE INTEGRATION IN ISOLATED SYSTEMS

2021

Horas de Autonomia do Sistema de Armazenamento de Energia	Nível de Penetração de Potência de energia renovável intermitente												
	0,22 MW	0,44 MW	0,66 MW	0,88 MW	1,32 MW	1,76 MW	2,2 MW	4,4 MW	8,8 MW	13,2 MW	17,6 MW	22 MW	44 MW
0,9 MWh	2%	3%	5%	6%	9%	13%	16%	28%	37%	40%	42%	43%	45%
1,8 MWh	2%	3%	5%	6%	9%	13%	16%	29%	38%	41%	43%	44%	46%
3,6 MWh	2%	3%	5%	6%	9%	13%	16%	30%	40%	43%	45%	46%	48%
7,2 MWh	2%	3%	5%	6%	9%	13%	16%	31%	43%	47%	49%	49%	52%
10,8 MWh	2%	3%	5%	6%	9%	13%	16%	31%	46%	50%	52%	53%	55%
14,4 MWh	2%	3%	5%	6%	9%	13%	16%	31%	49%	54%	56%	57%	59%
18 MWh	2%	3%	5%	6%	10%	13%	16%	31%	51%	57%	60%	61%	63%
21,6 MWh	2%	3%	5%	6%	10%	13%	16%	31%	53%	60%	63%	64%	67%
43,2 MWh	2%	3%	5%	6%	10%	13%	16%	31%	59%	76%	82%	85%	89%
64,8 MWh	2%	3%	5%	6%	10%	13%	16%	31%	60%	83%	93%	96%	99%
86,4 MWh	2%	3%	5%	6%	10%	13%	16%	31%	60%	86%	95%	98%	100%
108 MWh	2%	3%	5%	6%	10%	13%	16%	31%	60%	87%	96%	99%	100%
129,6 MWh	2%	3%	5%	6%	10%	13%	16%	31%	60%	88%	97%	99%	100%
151,2 MWh	2%	3%	5%	7%	10%	13%	16%	31%	60%	88%	98%	99%	100%
172,8 MWh	2%	4%	5%	7%	10%	13%	16%	31%	60%	89%	99%	100%	100%
194,4 MWh	2%	4%	5%	7%	10%	13%	16%	31%	60%	89%	99%	100%	100%
216 MWh	2%	4%	5%	7%	10%	13%	16%	31%	60%	89%	99%	100%	100%
237,6 MWh	2%	4%	5%	7%	10%	13%	16%	31%	60%	89%	100%	100%	100%
259,2 MWh	2%	4%	5%	7%	10%	13%	16%	32%	60%	89%	100%	100%	100%

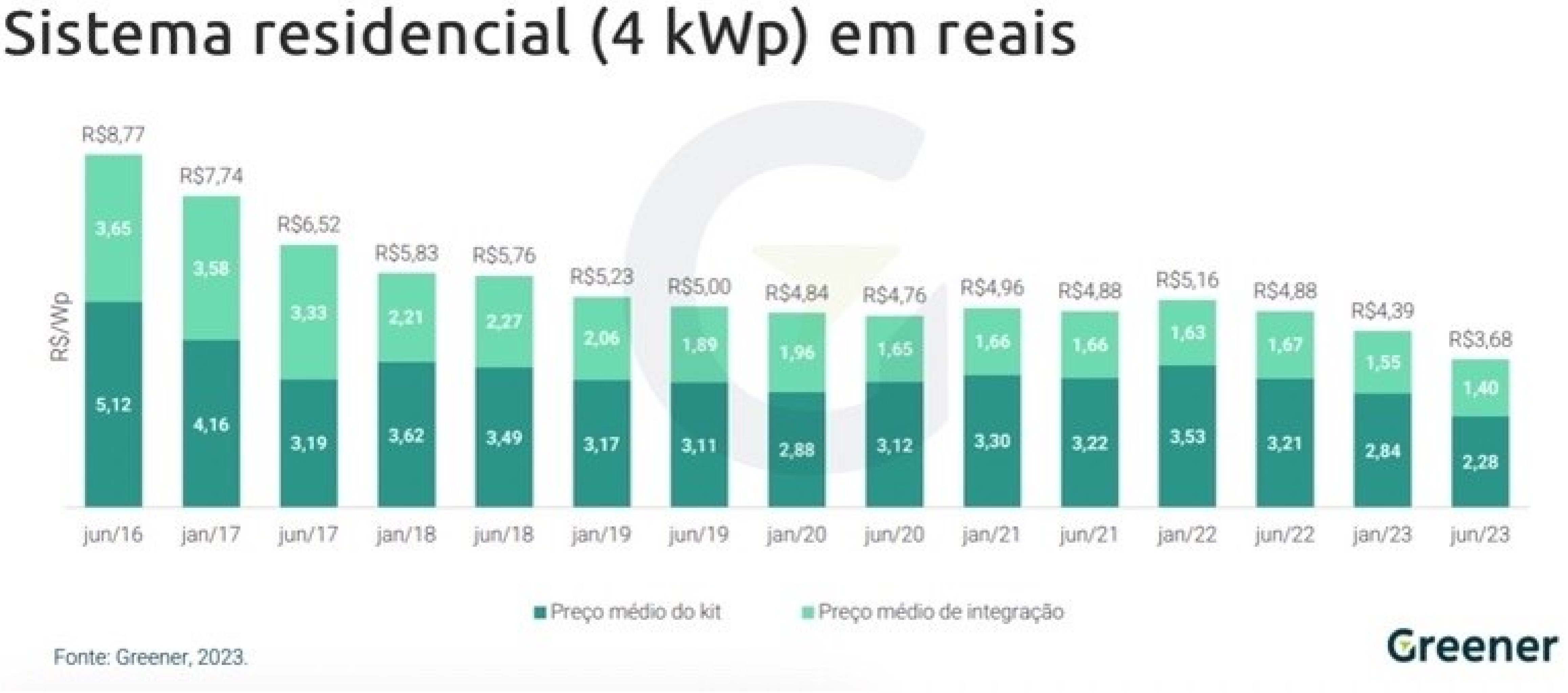




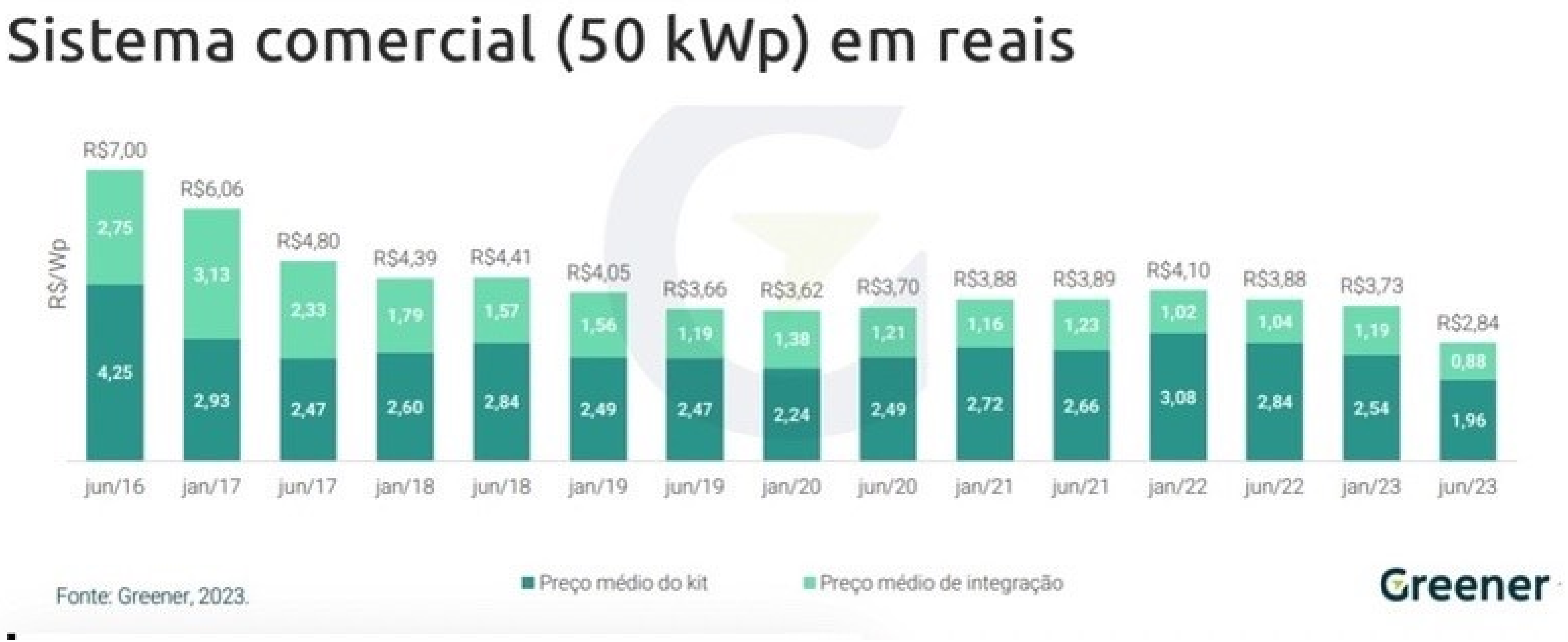
Feasibility Analysis for the Amazon Decarbonization

PV + Battery + Diesel

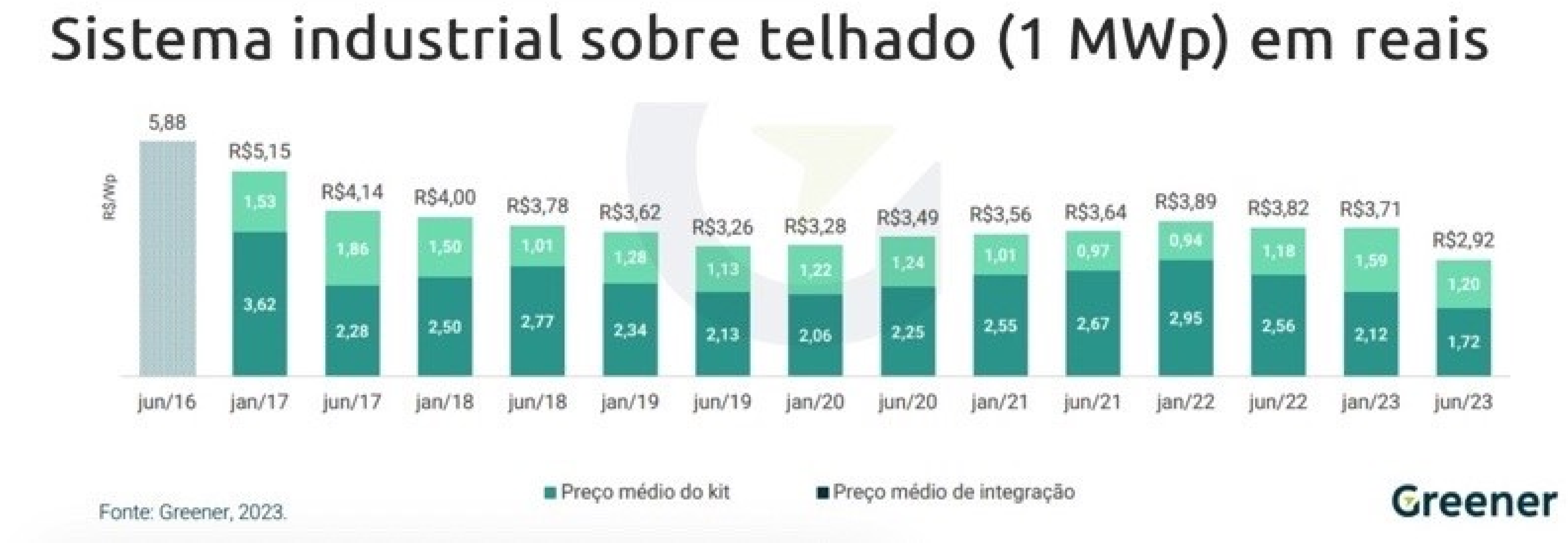
COST REDUCTION IS KEY



COST REDUCTION IS KEY



COST REDUCTION IS KEY



COST REDUCTION IS KEY

Residencial (4 kWp) – Baixa Tensão. Fonte: Greener