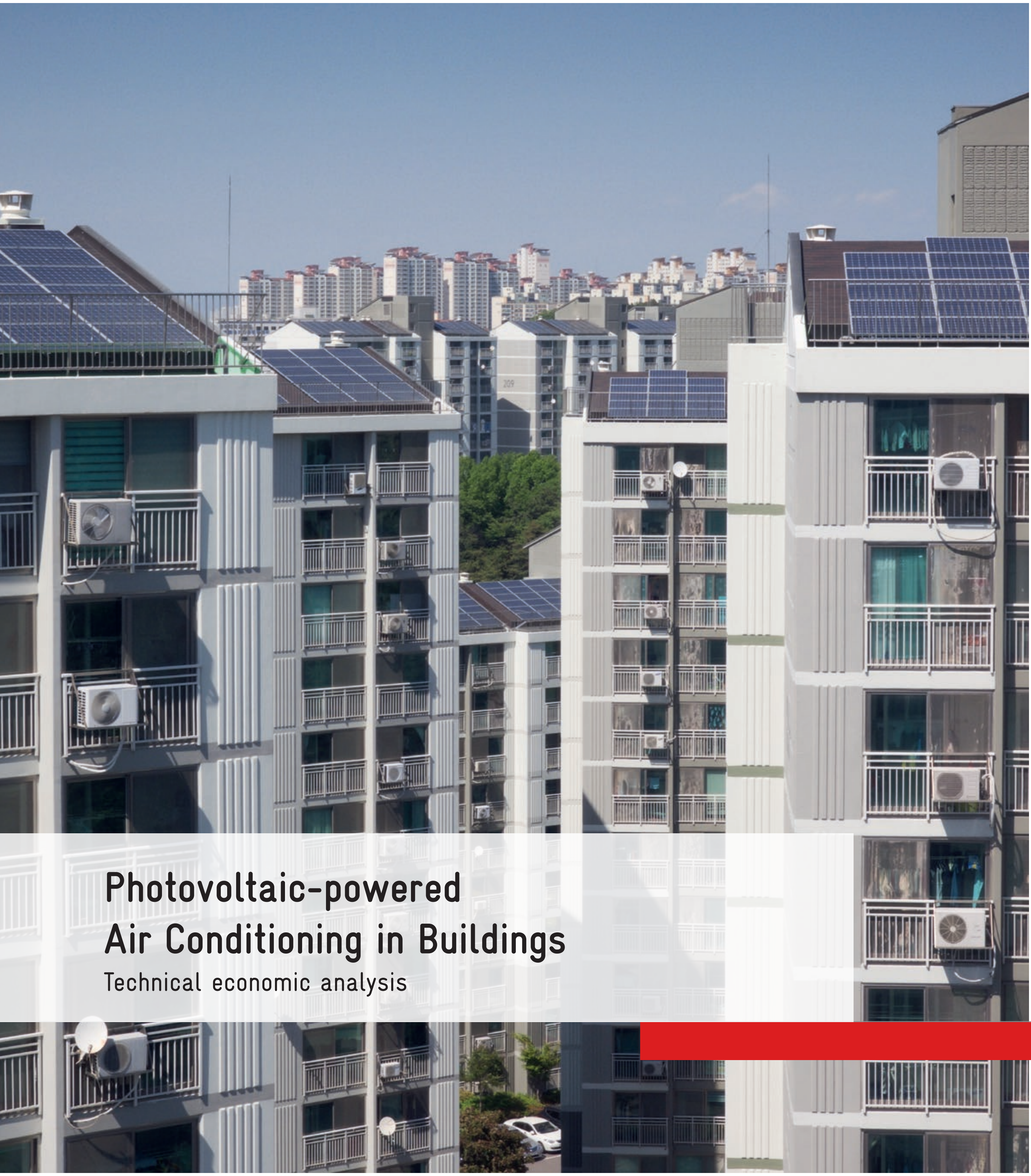

Photovoltaic-powered Air Conditioning in Buildings

Technical economic analysis

Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

On behalf of:

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Cool Contributions fighting Climate Change (C4)/ Proklima

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Table of Abbreviations

AC	Air conditioning
AGM	Absorbent Glass Mat battery
BMUV	German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety, and Consumer Protection (by their German acronym)
BTU/h	British thermal unit per hour, used as an alternative to kW (1 kW = 3412.12 BTU/h)
COP	Coefficient of performance
DC	Direct current
DEC	Desiccant evaporative cooling
EE	Energy Efficiency
EER	Energy Efficiency Radius
GHG	Greenhouse Gas
GIZ	Deutsche Gesellschaft für internationale Zusammenarbeit GmbH
GWP	Global Warming Potential
HC	Hydrocarbons
HCFC	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons
IPCC	International Panel on Climate Change
IDU	Indoor unit
KA	Kigali Amendment
LCOE	Levelized cost of energy
LFP	Lithium iron phosphate battery (LiFePO)
MP	Montreal Protocol
NDC	Nationally Determined Contributions
NMC	Lithium Nickel Manganese Cobalt battery
NPV	Net Present Value
ODS	Ozone Depleting Substance
ODU	Outdoor unit
PA	Paris Agreement
PCM	Phase change material
PV	Photovoltaic
RAC	Refrigeration and Air Conditioning
SEER	Seasonal Energy Efficiency Ratio
SDG	Sustainable Development Goals
VAT	Value added tax
VRF	Variable refrigerant flow

1. Introduction

Space cooling in buildings is characterized by enormous growth rates, due to increasing ambient temperatures, growing population and urbanisation. Air-conditioned buildings in many countries are largely dominated by mid to low appliance energy efficiency levels, highly climate-damaging refrigerants as well as fossil-fuel based electricity supply. This in sum generates a huge amount of greenhouse gas (GHG) emissions, furthering climate change.

Renewable energy sourced to operate efficient air conditioners using climate-friendly – natural refrigerants can play a critical role in significantly decoupling GHG emissions from a rapidly growing cooling demand in buildings, and thus contribute to the Paris Agreement climate targets. Further, driven by trends such as declining costs of solar PV and energy storage equipment, on the one hand, and efficiency improvements of AC technologies, on the other hand, solar-powered cooling is gaining an increasing technological and economic potential.

The objective of this paper is to further unfold the technical and economic potential of solar PV-powered green air conditioners. Therefore it focuses on the most widely applied type of active cooling appliance: single split-type air conditioning systems with a cooling capacity up to 5 kW. It looks at the current development of technical main components (AC, PV system, battery storage) and based on that defines model cases for hybrid and off-grid solutions for private and small commercial application. The technical and economic potential for these cases is then analysed for 13 countries by calculating the Levelized Cost of Electricity (LCOE) and the Net Present Value (NPV). Subsequently, a case study on Médecins Sans Frontières's (MSF) solar AC project in Haiti provides practical insights on the use of PV-powered AC systems in the context of off-grid social infrastructure.

Finally, this study shall contribute to further developing the highly potential but still infant PV AC market. It is meant as a starting point for further research and practical experience to be gained in the GIZ Proklima projects such as Cool Contributions fighting Climate Change II.

It has to be noted that the data for the country-level calculations have been gathered from existing studies and websites as well as through interviews with respective national authorities. Some data might be inaccurate or outdated due to misinformation.

2. Solar air-conditioning technologies

2.1. Passive cooling

Passive cooling refers to cooling systems without any external energy input. This technology solely depends on the building construction and must therefore be considered in the design phase of a new building. One option for passive cooling is a thick-walled building (e.g. with concrete walls and ceilings), which significantly reduces the influence of solar radiation and internal loads on the cooling demand. The heat capacity of the building envelope ensures thermal insulation that keeps the heat out of the building. A second option are phase-change materials (PCMs), which can be integrated into suspended ceilings or wall plaster. The building internal heat is stored in the PCM during the day, thus cooling the building. The heat is released into the building at night to be removed by passive ventilation, e.g. using open windows.

The PCM option can be applied to new and existing buildings without major retrofit effort. A third option are passive cooling systems that prevent external heat input into the building. These include shading devices, such as semi-transparent glass covers or awnings, as well as natural ventilation. Generally, passive cooling measures reduce the building's cooling load. Typically, passive cooling measures do not reduce the cooling load to zero. However, the remaining cooling load can be covered using a smaller active cooling system. In other words, every unit of heat that is prevented from entering the building through passive cooling measures will save electricity used by any active cooling system.

2.2. Active renewable cooling

Active renewable cooling refers to air-conditioning appliances driven completely or partially by renewable energy. Generally, a distinction can be made between thermal cooling systems (usually absorption chillers driven by solar heat) and electrical cooling systems (usually vapor compression chillers driven by solar electricity). Any renewable energy source (e.g. solar, wind, biomass, hydropower) that generates electricity can be used to operate electrical cooling appliances in a more climate-friendly manner. Solar energy (both solar heat and solar electricity) has evolved as the most obvious renewable energy source, given that cooling is especially required in regions with a lot of sun hours and typically high ambient temperatures.

Solar thermal cooling is not a new technology, it was first presented to the public at the 1878 World Exhibition in Paris (Mouchot, 1987). The technology itself has been experiencing a renaissance for the past two decades, fueled by climate change and the global goal of reducing the use of fossil energy sources. This has led to advances in the development of the technology itself (improved efficiency of sorption chillers and the systems, smaller volume chillers, improved system control, etc.).

Solar electrical cooling has become only recently an economically feasible alternative, mainly because of the significant price drop of photovoltaic systems over the last decade. It has evolved as a promising alternative to conventional grid-based compression refrigeration, especially in areas where grid electricity is generated from conventional energy sources at high costs and with high CO_2 emissions. Peak power demand for cooling/air-conditioning during the summer months can cause power grids to operate at maximum capacity or, in the worst case, fail. The application of solar cooling (both thermal and electrical) can thus take high electrical loads off the grid at peak times and support the reduction of greenhouse gas emissions in the building sector.

The technology combinations shown in *Figure 1* can be divided into water-based (closed) and air-based (open) systems. Air-based systems provide cool and dehumidified (conditioned) air, water-based systems provide refrigeration, chilled water or other chilled liquids.

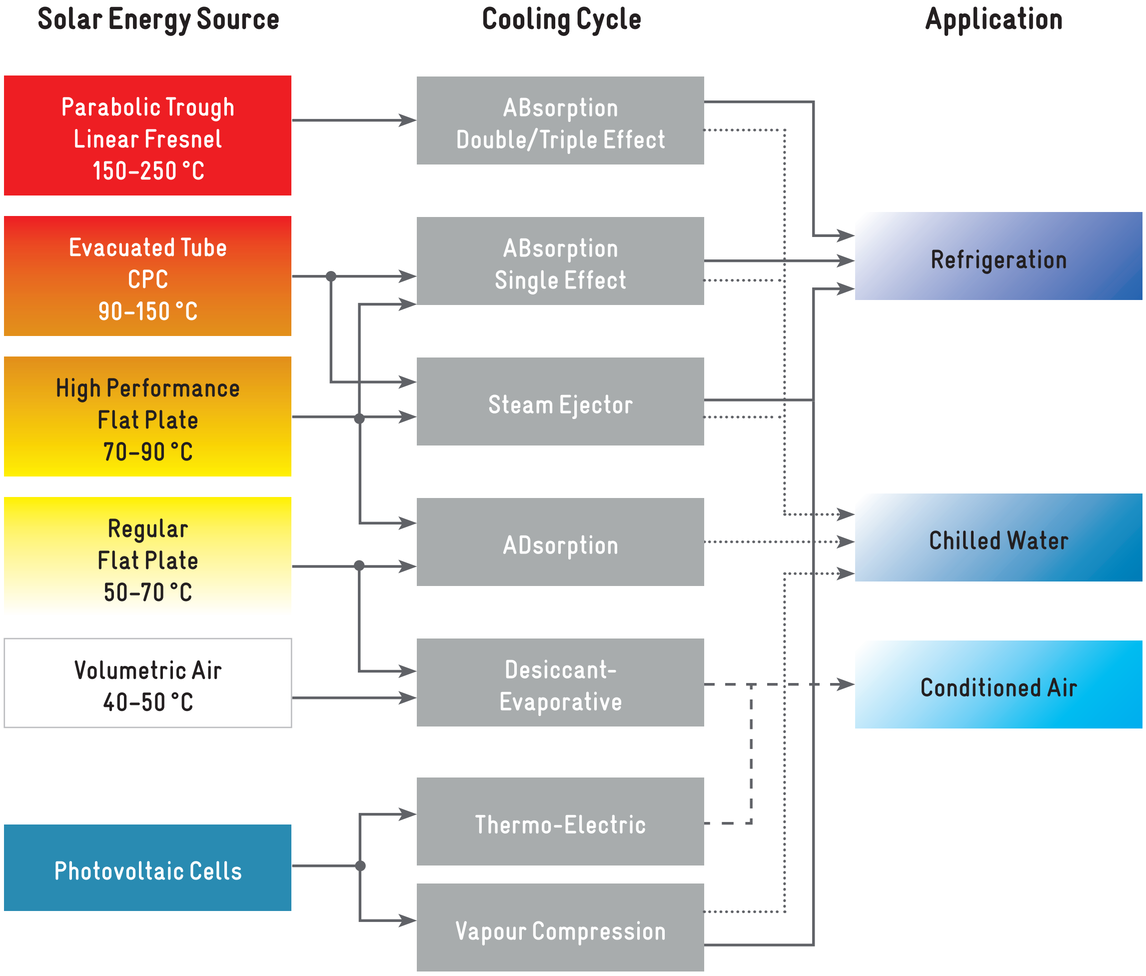

Figure 1: Overview of commercially available technology combinations for solar cooling.
(Source: Kohlenbach and Jakob, 2014)

With the photovoltaic option, a classification can be made regarding grid feed-in. Systems with feed-in tariffs supply the entire solar-generated electrical energy into the power grid and at the same time draw power from the grid to operate the cooling system. Systems with self-consumption, aka net-metering, initially supply the cooling system with solar-generated electrical energy and only feed any surplus into the power grid. Island systems have no grid connection at all. *Figure 2* shows the different PV air-conditioning options.

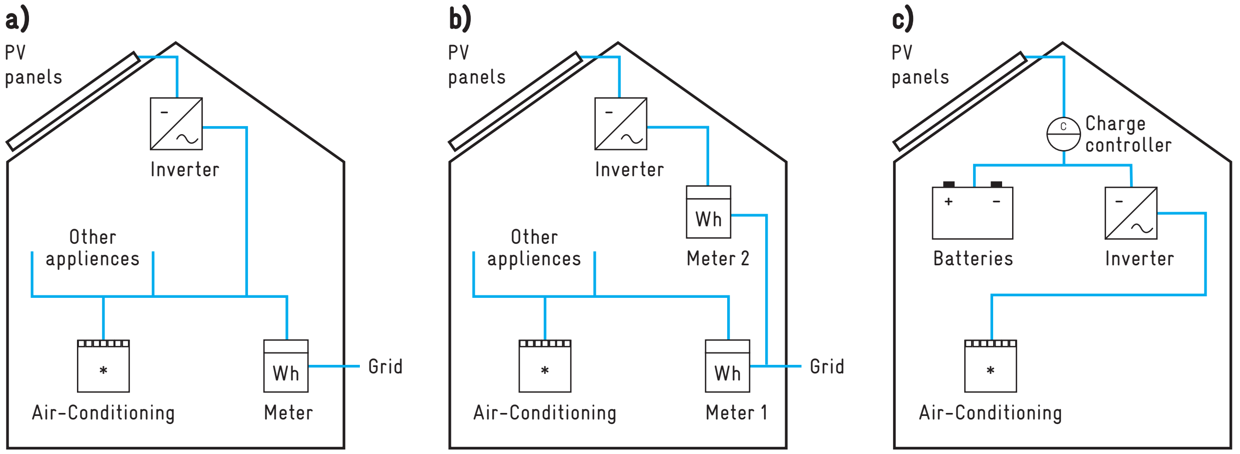

Figure 2: Different PV air-conditioning options: (a) Net-metering; (b) Feed-in Tariff; (c) Island system without grid connection. (Source: Kohlenbach and Jakob, 2014).

Today, five commercially available technology combinations for solar cooling are used globally.

1. Solar thermal operation of ABsorption and ADsorption chillers
2. Solar thermal operation of liquid sorption systems
3. Solar thermal operation of desiccant evaporative cooling (DEC) systems
4. Photovoltaic operation of vapor compression systems with feed-in tariffs
5. Photovoltaic operation of vapor compression systems with self-consumption

2.2.1. Solar thermal air-conditioning

Solar thermal air-conditioning is a combination of heat-driven ABsorption/ADsorption chillers, desiccant sorption wheels or liquid sorption using solar thermal heat as the main driving energy source. Heat is typically provided using non-concentrating solar thermal collectors, e.g. flat plate or evacuated tube collectors. These are quite common and have good commercial maturity. Concentrating collectors, e.g. parabolic trough or linear Fresnel collectors are able to supply higher temperatures up to 250 °C, however these are not very commonly used for solar thermal air-conditioning applications so far. This is mainly due to cost reasons. However, overall system efficiency can be improved, especially if using double-stage ABsorption chillers with this type of collector *(Figure 3)*. Typically, concentrating collectors are in use in countries where solar irradiation with a high share of direct radiation is present, e.g. China, India, Australia and Turkey.

Solar-driven ABsorption or ADsorption chillers use water or ammonia as refrigerant with no environmental impact in terms of Ozone Depletion Potential (ODP) and Global Warming Potential (GWP). These chillers require very little electricity for operation, compared to conventional chillers. The electrical coefficient of performance (COP) of current sorption chillers is greater than 10, e.g. only 0.1 kWh_{el} of electricity is required for 1 kWhr of refrigeration. Conventional vapor compression chillers have COP's between 2 and 3 on average, hence the electricity requirement is on average 0.33 to 0.5 kWh_{el} for 1 kWhr of refrigeration. The operating cost (OPEX) of sorption chillers is therefore lower than for conventional chillers. Also, depending on the energy mix for electricity production in the country under consideration, they have significantly lower equivalent CO_2 emissions than vapor compression chillers.

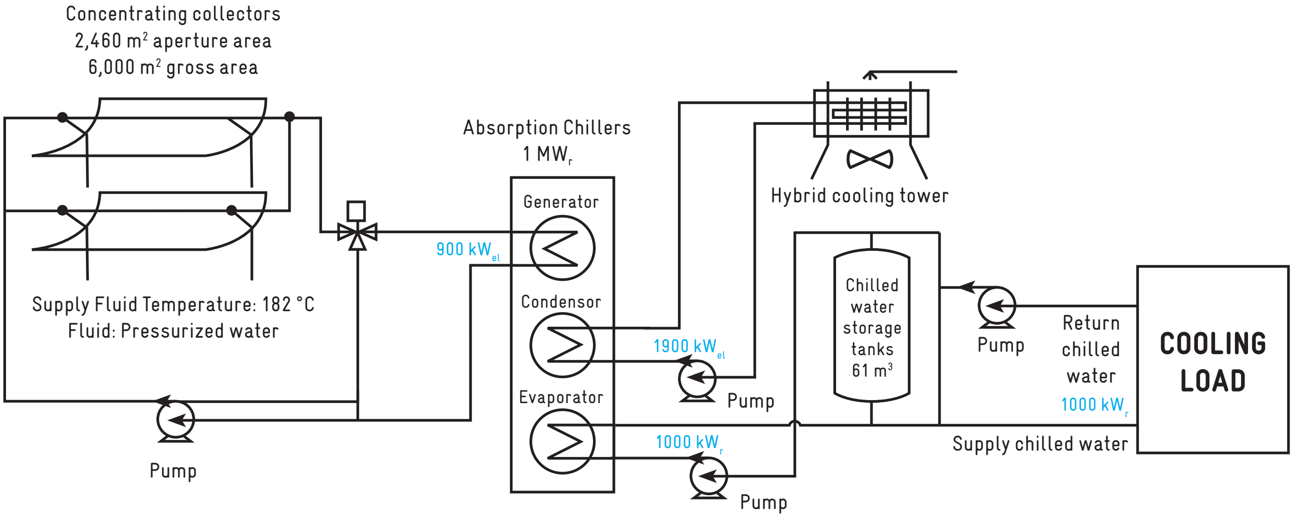

Figure 3: Schematic of a solar thermal air-conditioning system using concentrating collectors with absorption chiller. (Source: SOLEM Consulting)

Other components are required in a solar thermal system in addition to the solar collectors and cooling components. Thermal storage is helpful to smoothen the fluctuation of solar resource over the day and provide improved adaptation to building cooling demand. Thermal storage devices are commercially available in all sizes and various technologies, e.g. hot water storage, phase change material (PCM) storage and ice-storage. Furthermore, components for the heat rejection of thermal chillers are required. Depending on the ambient conditions, these differ in their functionality (dry, wet or hybrid coolers). All components of a solar thermal cooling system are mature technologies and commercially available on the global market.

2.2.2. Solar PV air-conditioning

Solar photovoltaic (PV) air-conditioning is the second technology that uses solar energy to generate cold – the focus of this study. It is a combination of PV modules and conventional electrical chillers, e.g. vapour compression chillers. Other components required are heat rejection devices, just like for thermal chillers. Depending on the ambient conditions, these again differ in their functionality (dry, wet or hybrid coolers). Electrical energy storage can be implemented via batteries, see *Chapter 2.2.2.2* for more information on battery storage. All components of a solar electrical cooling system are mature technologies and commercially available on the global market. *Figure 4* shows a generic PV cooling system using self-consumption and battery storage.

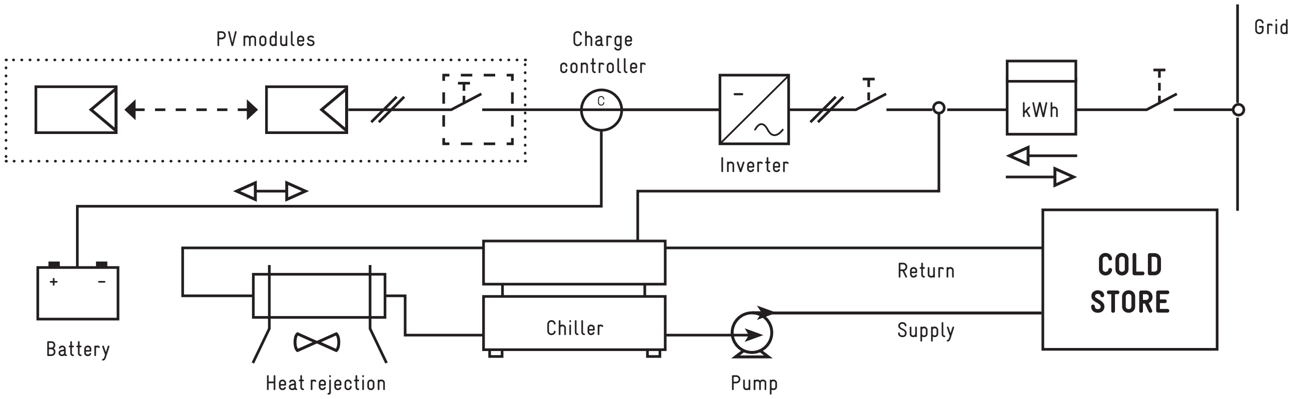

Figure 4: Schematic of a PV cooling system with self-consumption, indirect cooling and battery storage. (Source: SOLEM Consulting)

When using vapor compression chillers, two options for cooling a building are possible: indirect cooling via a chilled water loop or direct cooling via evaporation of a refrigerant (such as in a split-type air conditioning system).

Indirect cooling uses a chilled water loop from the vapor compression chiller to the building to extract heat from the building. This technology is implemented in medium and larger systems for multiple rooms or large buildings. *Figure 4* shows a solar PV air-conditioning chiller scheme with indirect cooling, where electrical energy from the PV panels drives the vapor compression chiller. A water loop (no refrigerant) is used to extract heat from the building.

Direct cooling consists of liquid refrigerant being pumped through pipes into the building and refrigerant vapor being extracted from the building, thereby generating the heat transfer. This technology is implemented in both small and larger systems for one or multiple rooms or small buildings. If only one room is air-conditioned the units are called split or mini-split units (refer to *Chapter 2.2.2.1* for more information). For larger buildings, several individual evaporator units are used, typically one per room. These systems are referred to as VRF (variable refrigerant flow) systems. *Figure 5* shows a direct expansion VRF system. Electrical energy from the PV panels is used to drive the VRF system. If the PV modules generate more energy than is currently required, the excess is fed into the power grid. Conversely, electricity is drawn from the grid if the PV system does not provide enough energy for cooling. The heat extracted from the building or process is usually transferred to the environment via a heat rejection unit.

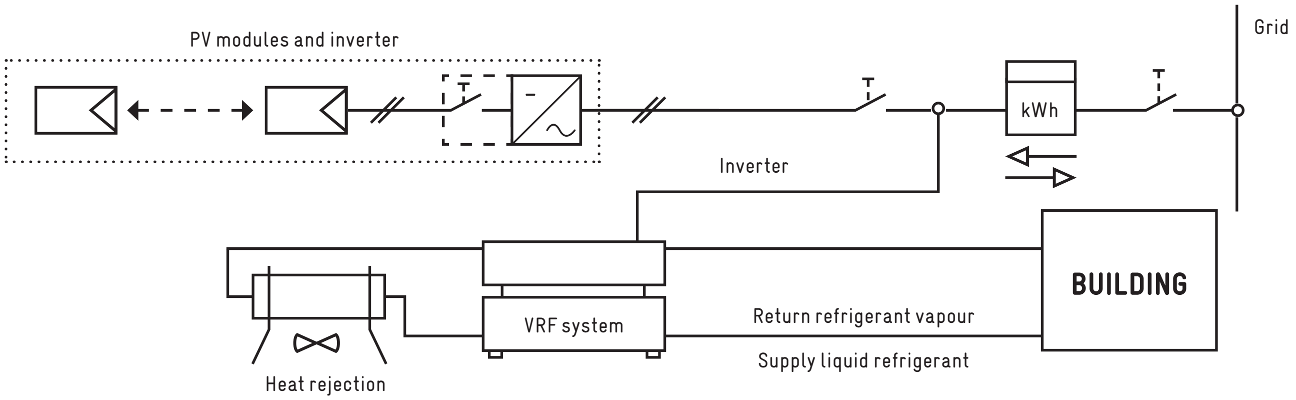

Figure 5: Schematic of a PV cooling system with self-consumption and direct cooling. (Source: SOLEM Consulting)

2.2.2.1. Split Air Conditioners

(Ductless) single-split ACs, also known as mini-splits, typically have a cooling capacity up to 7 kWr, accounting for about 70% of all ACs used to cool building space worldwide. A single-split AC consists of an indoor unit (IDU) and an outdoor unit (ODU). The indoor unit (IDU) is mounted on the wall inside the air-conditioned room. It includes an evaporator and a fan. The outdoor unit is installed outside, and it contains a compressor, condenser, fan, and expansion device. The indoor and the outdoor unit are connected by refrigerant piping and electrical cables.

Figure 6 depicts the relevant components of a solar PV-powered split-type air conditioning system in off-grid and hybrid mode.

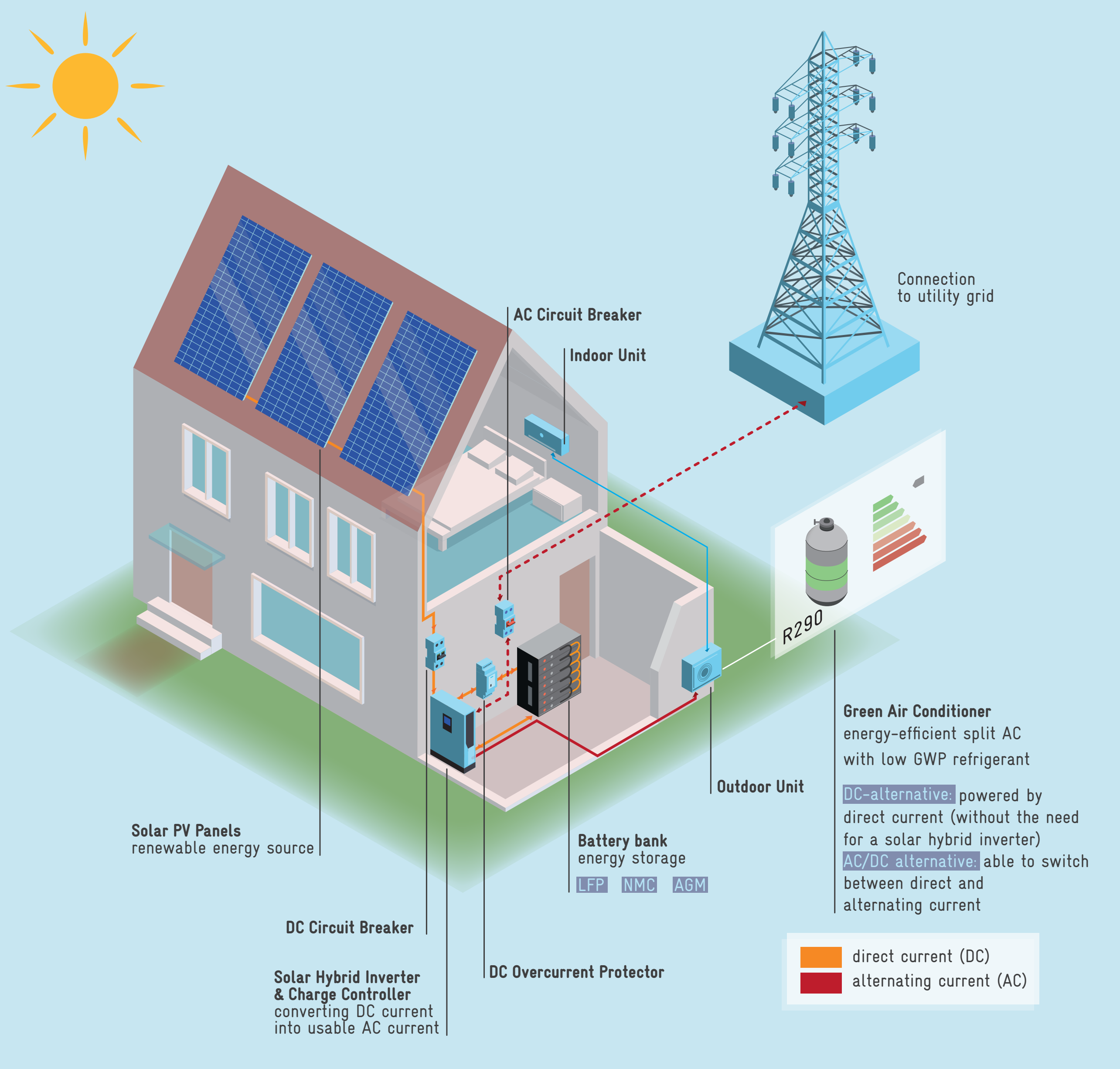

Figure 6: Components of off-grid and hybrid solar air conditioner systems (Source: GIZ Proklima).

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In more moderate climates split AC technology is offered with a cooling and heating mode in one reversible system. However, the vast majority of split ACs around the world are used for cooling purposes only. Split ACs can be found in various types of buildings, including private households, public buildings such as hospitals as well as commercial premises such as office buildings, hotels, shops, or restaurants. They are easy to install in existing buildings, requiring comparably low investment cost and enable individual control of cooling setting in each room.

The most relevant technology difference in split ACs results from the compressor control: fixed speed or variable speed. With fixed speed compressors, there is only one mode, which can be either turned on or off. In variable speed (also called inverter) compressors, the speed – and thereby the intensity of cooling – can be run in part load to reach or maintain the desired temperature. Inverter technologies achieve higher efficiencies as they are optimized for part-load operation. GHG emissions from split ACs are composed of emissions due to the use of electrical energy for operation and emissions due to leakage. The latter usually amounts to one third of the total lifetime GHG emissions of split AC units and is thus a considerable problem. Typical refrigerants used in split ACs are shown in *Table 1*. The higher GWP of HCFC or HFCs as refrigerants results in significant GHG emissions released into the atmosphere. Consequently, there is a global shift to green cooling, using hydrocarbons as refrigerants with low GWP. R290 (propane) is currently the only climate-friendly HFC-alternative refrigerant used for single split-type ACs (GIZ and Umweltbundesamt, 2019).

The vast majority of all single split ACs is driven by alternating current (AC) power, since this is the global electricity grid standard. For off-grid applications as well as electric vehicles direct current (DC) powered split ACs are also commercially available. PV panels generate direct current (DC), hence the combination of PV and AC units depends on the type of current of the respective AC unit. If an AC unit powered by alternating current is chosen, PV-generated direct current needs to be inverted to alternating current, which incurs a small loss due to the electrical inversion (approx. 1-2%). If a direct current AC unit is chosen, PV generated direct current can be used without inversion. This option may sound less complex, but it is typically less attractive from an economical point of view due to the generally higher investment cost of DC air-conditioning units. A third alternative are AC/DC hybrid air-conditioning units, which can switch between direct and alternating current. However, hybrid AC units using R290 are not yet commercially available.

Type	R-Number	GWP_{100}	Source
Hydrochlorofluorocarbon (HCFC)	R22	1,760	IPCC Fifth Assessment Report, 2014
Hydrofluorocarbon (HFC)	R32	677	IPCC Fifth Assessment Report, 2014
Hydrofluorocarbon (HFC)	R410A	1,924	IPCC Fifth Assessment Report, 2014
Hydrocarbon (HC)	R290	1	IPCC Fourth Assessment Report, 2007

Table 1: Refrigerants used in split ACs.

The green cooling option applied to single split AC needs to fulfil two fundamental criteria in order to meet necessary emission reductions:

1. Use of a climate-friendly refrigerant with a GWP less than 10
2. Use of a high energy efficiency AC unit
(at least the top star label category in the target country)

2.2.2.2. Electricity storage technologies

Off-grid solar PV systems rely on batteries to store electricity generated during sun hours, e.g. for night-time cooling. Hybrid solar PV systems with grid connection can use batteries as a backup and to store excess electricity, especially if feeding electricity into the grid is less profitable than self-consumption. Driven by an increasing demand for decentralized energy production and consumption, the battery market has made rapid technological progress over the past decade. Until recently, lead-acid batteries have been widely used for electricity storage in solar PV systems as they are cheap, robust, and generally available. However, as a result of continuously falling lithium-ion (li-ion) battery prices, lead-acid batteries have rapidly been replaced in many markets. Currently, li-ion batteries are the most widely used electricity storage technology (IEA, 2021).

Among the lead-acid battery type, absorbent glass mat (AGM) batteries are considered most suitable for solar PV systems. Flooded lead-acid batteries are cheaper than AGM, but they are designed for the use in cars, and require maintenance. Among the li-ion batteries, lithium iron phosphate (LFP) and lithium nickel manganese cobalt (NMC) oxide batteries are the most relevant ones for solar applications. *Table 2* provides an overview of the main characteristics of the three battery technologies, including purchasing price, efficiency, lifetime, safety, and environmental impact.

Li-ion batteries offer several advantages, such as longer lifetime and better performance (i.e. higher depth of discharge and higher efficiency) compared to lead-acid batteries (IRENA, 2017). NMC have the greatest energy density among the three technologies, making them a preferred choice for electric vehicles, where weight and space are crucial. LFP have a relatively high energy density as well, significantly higher than AGM. Lead-acid batteries have a lower purchasing price, which is the primary reason keeping them competitive with li-ion alternatives. Though the higher price of li-ion batteries is often offset by longer lifetime.

From an environmental perspective, lead-acid batteries are favorable compared to li-ion batteries given their high recycling rates of up to 99 % (GIZ, 2018). Progress in recycling of li-on batteries is necessary as increasing amounts of batteries reach the end of their life. Regarding the use of raw materials, LFP have a lower environmental impact compared to NMC as they contain neither cobalt nor nickel. Moreover, LFP use non-toxic electrode material, in contrast to AGM and NMC. Nevertheless, their reliance on lithium as critical mineral raises environmental (and social) concerns.

Other technologies such as Redox flow batteries present an environmentally friendlier alternative to li-ion batteries due to their lack of reliance on lithium, cobalt, or nickel. They also offer a lower sensitivity to high depth of discharge, long lifetime, large energy capacity, but their energy density is lower compared to li-ion batteries, and they are not yet commercially mature (IEA, 2021).

Overall, li-ion batteries are the most suitable storage technologies for small-scale solar PV systems on today's battery market. In hybrid systems, where battery storage is only rarely used as backup, or in case of limited financial resources to cover upfront costs, lead-acid batteries such as AGM may be recommended as they meet storage needs while saving costs. In off-grid systems, where batteries are used as primary energy storage, as well as in hybrid systems that require batteries for everyday use, li-ion batteries are most advantageous, in particular LFP as their price is falling fastest.

	Li-ion batteries		Lead-acid battery
	Lithium iron phosphate (LFP)	Lithium nickel manganese cobalt (NMC)	Absorbent glass mat (AGM)
Purchasing price	+/– • High, but falling • In 2021, on average, 30% cheaper than NMC • May be offset by longer lifetime	– • High, but falling • May be offset by longer lifetime	+ • Cheapest, but more expensive than flooded lead-acid
Efficiency[2]	+ 92–96 %	+ 92–96 %	+/– 88–92 %
Lifetime	++ 3000 and more cycles[3]	+ 2000–4000 cycles[4]	– 500–1500 cycles[5]
Product safety[6]	+ • Highest thermal stability among li-ion batteries • If installed properly, hazard risk can be minimized.	+/– • Slightly lower thermal stability than LFP • If installed properly, hazard risk can be minimized.	+ • Lower risk of thermal runaway than li-ion batteries
Environmental impact	– • Reliance on lithium • Non-toxic cathode material • Low recycling rates	– – • Reliance on cobalt, nickel, lithium • Toxic cathode-material • Low recycling rates	– • Toxic electrode-material (lead) • Recycling rates up to 99 %

Table 2: Comparison of battery technologies relevant for small-scale solar PV systems.

[1] Bloomberg NEF (2021)

[2] https://couleenergy.com/best-batteries-for-solar-pv-system/

[3] https://offgridtech.org/tech-updates-online/2021/lithium-iron-phosphate-batteries-pros-and-cons/

[4] https://www.victronenergy.com/blog/2015/03/30/batteries-lithium-ion-vs-agm/

[5] https://www.victronenergy.com/blog/2015/03/30/batteries-lithium-ion-vs-agm/

[6] GIZ (2018), IRENA (2017)

[7] GIZ (2018)

2.2.2.3. Photovoltaic panels

Photovoltaic panels (sometimes also called modules) have evolved into a mass-produced product and therefore significantly fallen in price over the last decade.

Five PV panel types are currently common for roof systems:

1. Monocrystalline PV panels
2. Polycrystalline PV panels
3. Thin film PV panels with amorphous silicon (a-Si)
4. Thin-film PV panels with cadmium telluride (CdTe)
5. Copper Indium Diselenide (CIS)/Copper Indium Gallium Diselenide (CIGS) PV panels

Monocrystalline PV panels are said to have the highest levels of efficiency to date, at up to 20 percent. During production, the silicon is melted two times and then rods are pulled out of the melt with a so-called seed crystal while rotating. Since there is no different crystal orientation, there are no grain boundaries in the wafer and there are fewer losses. This ensures higher efficiency. Its lifespan is estimated at a good three decades.

Polycrystalline solar panels are easy and cheap to produce. To do this, silicon is melted, "doped" with boron atoms and then cast into square blocks, the ingots. As the semiconductor material cools, it crystallizes and forms a large number of crystal structures that differ greatly in shape and size.

Thin-film cells are manufactured very differently from crystalline solar cells. A carrier material (usually glass, more rarely foil) is steamed or sprayed with a thin layer. Thin-film solar cells are around 100 times thinner than crystalline solar cells made from silicon wafers. They deliver good and constant solar power yields even with weak or diffuse irradiation and comparatively high temperatures. Even shading has less critical effect on thin-film panels. *Table 3* gives an overview on PV panel characteristics.

PV panels	Mono-crystalline	Poly-crystalline	Thin film amorphous silicon	Thin film cadmium telluride	CIS/CIGS
Purchasing price	High, because of complex production process	Cheaper, but less efficient than mono-crystalline panels	Cheapest, but lowest efficiency, so panels only pay off on large areas	Middle, particularly suitable for diffuse irradiation	High, medium efficiency
Efficiency	14–20 %	12–16 %	5–7 %	6–8 %	12–15 %

Table 3: Characteristics of PV panels.

2.2.2.4. Inverter and control devices for off-grid and hybrid solutions

Inverters convert the direct current (DC) generated by the PV panels into alternating current (AC). This conversion is necessary because the power grids and domestic power lines work with AC. After conversion in the inverter, the electricity from the PV panels can then be fed directly into the grid or used in the building.

However, modern inverters can do much more. In addition to power conversion, they will take on a wide range of tasks, from control (regularly monitor the voltage, frequency and impedance in the grid) and performance optimization (inverter manages to keep the PV panels constantly in the Maximum Power Point (MPP) by changing the internal resistance at regular intervals) to energy management (monitoring of voltage, current and current output of the system to identify quickly malfunctions and forward yield data to corresponding online services or energy management system). These help PV system owners to use more of their own electricity. Another option is a hybrid inverter, which is a hybrid solution between an inverter and a solar battery to increase the share of self-consumption in the total amount of electricity produced. *Table 4* shows inverter options for PV systems.

The general design rule is to oversize the total panel power compared to the inverter power by about 10% (better partial load behaviour and thus its improved annual efficiency).

	Module inverter	String/Multistring inverter	Central inverter
Inverter specifications	• Directly attached to the individual PV panel • Advantageous for small mobile PV systems (off-grid) in which the light and shadow conditions change frequently • In large PV systems they are very susceptible to faults due to the large number of devices and increased potential for errors • Complex maintenance and replacement • Do not have to be wired via DC • Use 50% less cable compared to conventional PV systems	• Most commonly used • Operates several PV panels connected in series, so-called string • Panels with the same orientation, inclination and shading are combined • One MPP tracker per string • Simplified maintenance as the inverters can no longer be placed on the roof, but in the building services room • By bundling panels under the same conditions, mismatching losses and shading losses are minimized	• Mostly used in very large roof or ground-mounted systems (only one inverter) • All panels are subject to similar inclination and irradiation conditions • The panel strings can be brought together centrally via a generator connection box • Maintenance is greatly simplified • Often remote maintenance contracts in which the system is permanently digitally monitored • Power from a central inverter can be fed directly into the medium-voltage grid.

Table 4: Inverter options for photovoltaic systems.

3. Drivers for PV-powered air conditioning

Renewable energy sourced to operate green air-conditioning can play a critical role in sufficiently decoupling GHG emissions from a rapidly growing cooling demand in buildings, in accordance with the Paris Agreement climate targets. Further, driven by trends such as declining costs of solar PV and energy storage equipment, on the one hand, and efficiency improvements of AC technologies, on the other hand, solar-powered cooling is gaining an increasing technological and economic potential. *Figure 7* provides an overview of key drivers for PV-powered air conditioning.

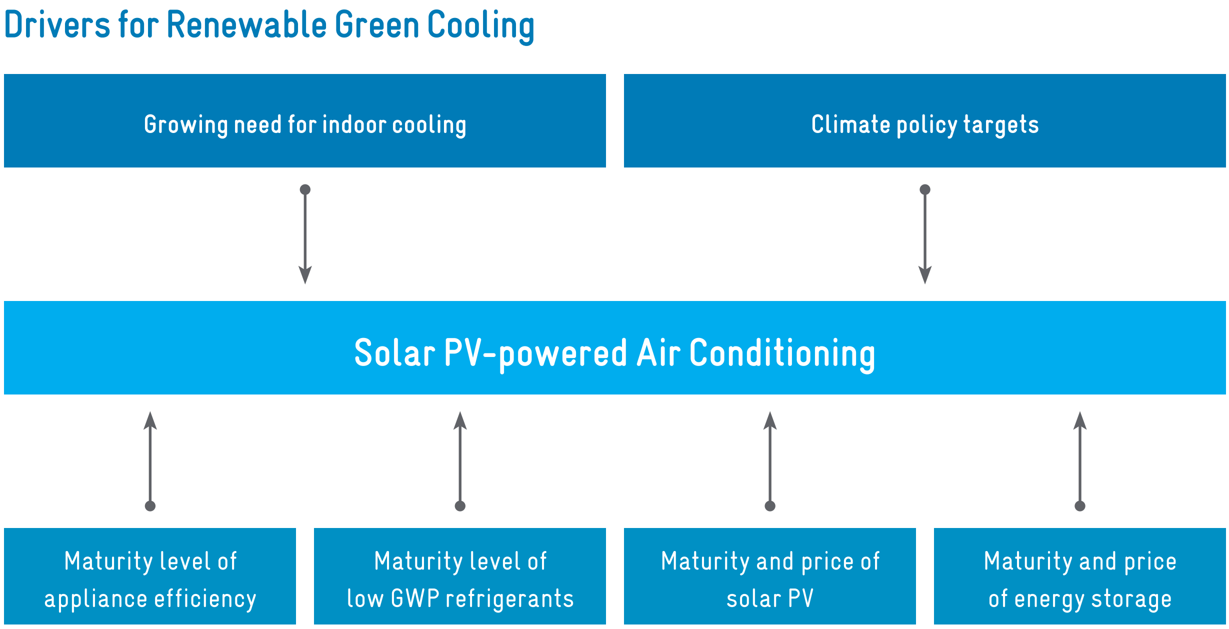

Figure 7: Drivers for Solar-powered Air Conditioning. (GIZ Proklima, 2021)

3.1. Growing demand for space cooling

The demand for cooling, especially to cool building space, is growing rapidly due to a rising middle class, urbanisation, changes in workspace, an increasing population, and rising temperatures. Globally, the absolute number of Room ACs in use is expected to rise from just over 850 million in 2016 to over 3.7 billion in 2050 (IEA, 2018).

Promoting passive cooling by implementing urban planning measures and adapting building design to the local climate has a huge potential to slow down the growth of the cooling demand. However, the existing building stock, especially in developing and emerging countries with high ambient temperatures, are locked-in by low insulation standards and architecture which doesn't allow for passive cooling. This will drive active cooling demand, at least over the next two decades. Avoiding or reducing the need for active cooling is the preferred medium- to long-term strategy, given the required time to transform the current building stock. In order to decouple growing GHG emissions from the existing and still growing "active cooled building stock", short-term action on using renewable energy sources, improved AC appliance efficiency and transition to low global warming refrigerants is required.

3.2. Climate policy targets

To enter development pathways compatible with the Paris Agreement objective of limiting the global temperature rise to well below 2 °, there is an urgent need to decarbonize the cooling sector. The cooling sector is estimated to account for 13 % of global GHG emissions by 2030 (GIZ, 2015). This includes indirect emissions from fossil-fuel based electricity consumption as well as direct emissions from the use of refrigerants with high global warming potential (GWP). According to IEA (2018), space cooling accounted for around 10 % of the total electricity demand worldwide in 2016. In a business-as-usual scenario, the energy demand from AC systems will more than triple by 2050.

The Montreal Protocol (MP) regulates the international phase-out of ozone-depleting refrigerants, such as hydrochlorofluorocarbons (HCFC). Hydrofluorocarbon (HFC) refrigerants with high GWP are subject to the Kigali Amendment (KA) to the MP, adopted in 2016. The KA regulates the global phase-down of HFC refrigerant production and consumption. The widespread use and leakage of HFC and HCFC refrigerants in AC technologies adds a significant amount of direct emissions. Global implementation of the KA would prevent up to 80 billion tonnes CO_2-eq of emissions by 2050 (EC, 2018).

Promoting energy efficient green ACs in combination with solar energy sources offers a significant opportunity for countries to comply with the KA as well as to contribute to national climate action plans (Nationally Determined Contributions).

3.3. Maturity level of appliance efficiency

Increasing efficiency of AC technologies, especially split AC systems, makes PV-powered solutions more and more viable. Energy efficiency of split ACs is mainly determined by compressor performance and the size of the heat exchanger. For instance, variable speed compressors represent an energy-efficient alternative to fixed speed compressors, which only operate in on/off mode. The former can adapt the cooling capacity to part loads with slight changes in cooling demand. Moreover, the amount of heat transferred by the heat exchanger can be optimised by increasing its surface area and the choice of material (GIZ, 2019). Further details and measures to improve energy efficiency are described by Usinger (2016).

Global coverage of mandatory AC energy performance standards doubled worldwide in the last 15 years. Nevertheless, there is enormous remaining potential to reduce energy consumption. Globally, over 40% of energy used for air conditioning can be saved by applying international best practice standards and additional 20 % by applying best available technologies (GIZ, 2019).

3.4. Maturity level of low GWP refrigerants

Low GWP refrigerants are available and increasingly being adopted driven by the global phase-out of HCFCs under the MP and the phase-down of HFCs under the KA. A climate-friendly refrigerant alternative for split ACs is propane, a naturally occurring gas with a GWP of 3. Propane has highly favourable thermodynamic properties and can be used as an energy-efficient refrigerant, designated R290. The use of R290 in energy efficient AC systems minimizes electricity needs for cooling, making solar PV-powered ACs more viable, especially off-grid solutions.

Due to its flammability, the use of R290 refrigerant requires additional safety precautions for installation and servicing of AC systems, including charge size limitations, which represents a barrier for widespread adoption thus far. However, through risk mitigation measures, adequate safety standards and the employment of qualified technicians risks can be significantly reduced. Moreover, higher energy efficiency of the R290 refrigerant typically offsets additional cost. Further details on R290 Split ACs, including technical design, safety standards and manufacturing, are compiled by GIZ and Umweltbundesamt (2019).

3.5. Maturity and price of solar PV

The cost for solar PV technologies declined over 2010 – 2019 at 82 %, and are predicted to further decrease (IRENA, 2020). It is foreseeable that solar power in combination with local or central electricity storage solutions will become the most competitive source of energy supply. Furthermore, timeframes of solar radiation and the need for comfort cooling largely overlap, providing a huge potential for the direct use of PV solar energy for air conditioning. Another co-benefit is the reduction of stress on the utility grid caused among others by high electricity demand for cooling, especially in countries with frequent power outages.

3.6. Maturity and price of energy storage

The lack of affordable energy storage technologies has long presented a challenge for the adoption of solar PV in residential and small-scale commercial applications. Driven by technological developments over the past decade, however, the cost of batteries has drastically decreased. Quality battery storage is now economically attractive, with costs ranging from $ 400 per kWh to $ 750 per kWh. The cost could decrease in stationary applications by another 54–61 % by 2030 compared to 2016, e.g. 61 % for LFP batteries (IRENA, 2017). Moreover, the declining costs of stationary battery systems are also driven by spillover effects from the rapid development of batteries for electric vehicles (Tsiropoulos et al., 2018).

In 2021, rising raw material prices due to global supply chain disruptions and increasing demand have led to short-term rises in battery prices (BloombergNEF, 2021). However, the cost of lithium and other raw materials only contributes a fraction to the overall battery costs, which limits the impact of future raises in raw material prices.

4. Assessment of the solar cooling potential in selected countries

The focus of this chapter is the assessment of the technical and economic potential for PV-powered green air-conditioning in selected countries. This assessment is done for two main scenarios using a modular, unit-based approach:

- a residential building
- a small commercial building

Both scenarios are considered to be the smallest commercially feasible solutions for the given purpose of room air-conditioning. They can however be extrapolated to larger buildings by multiplying the results in a modular approach. Both scenarios have been investigated for two options:

- Hybrid (PV system with grid connection and net-metering, without battery storage)
- Off-grid (PV system without grid connection, with battery storage)

Table 5 shows the main parameters assumptions in each green AC scenario. For the scenarios below, technical designs, cost and performance results have been evaluated. The results have been compared to conventional air-conditioning using 100% grid power (base case scenario).

GREEN AC		Hybrid option		Off-grid option	
Scenario	AC cooling capacity	PV peak power	Battery size	PV peak power	Battery size
	kW_{th}	kW_{p}	kWh_{el}	kW_{p}	kWh_{el}
Residential house	2.5	1.0	–	1.0	2.0
Small commercial building	5.0	2.0	–	2.0	2.5

Table 5: Scenario overview – Green air-conditioning

4.1 List of countries

GIZ Proklima is promoting Green Cooling through different projects in various partner countries worldwide. Partner countries investigated in this study were selected based on size and growth rate of their space cooling market.

- China
- Colombia
- Costa Rica
- Ghana
- Grenada
- Honduras
- India
- Iran
- Kenya
- Philippines
- Senegal
- Thailand
- Viet Nam

4.2. Assessment framework

Both scenarios have been investigated using dynamic economic analysis. Technical parameters and yield of PV and battery systems have been evaluated using software-based annual performance simulations with an hourly resolution.

4.2.1. Technical design

The following technical assumptions have been made for the scenarios.

		Green Air-conditioning (higher appliance efficiency and R-290 refrigerant)		Conventional Air-Conditioning (base case)	
		Residential house	Small commercial building	Residential house	Small commercial building
Parameter	Unit				
Average annual energy efficiency ratio of AC unit (EER)[8]	-	4.0	4.0	2.5	2.7
Refrigerant (GWP)	$CO2_{eq}$	R290 (1)	R290 (1)	R410a (2088)	R410a (2088)
AC nominal cooling capacity	kW_{th}	2.5	5.0	2.5	5.0
AC nominal electrical power consumption	kW_{el}	0.625	1.25	1.0	1.85
PV peak power installed on roof	kW_{p}	1.0	2.0	-	-
Lifetime of plant (AC and PV components)	a	20	20	20	20
Interest rate	%	5.0	5.0	5.0	5.0
PV module degradation (efficiency drop)	%/a	0.8	0.8	-	-
Grid electricity price change	%/a	1.0	1.0	1.0	1.0
Consumer price index (CPI)	%/a	1.0	1.0	1.0	1.0
PV OPEX as % PV CAPEX	%	1.0	1.5	-	-
AC unit cost	€	450	550	300	400

Table 6: Technical assumptions for green and conventional scenarios.

All PV systems have been assumed with an azimuth due south (0°) and optimized module slope per latitude. Modules used in the simulations were polycrystalline modules of average quality to account for a global average. The air-conditioning load was modeled using annual values of air-conditioning hours per country and a weekly/monthly demand profile. See *Annex 8.1* for details on air-conditioning load profiles used in the simulations.

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[8] Note that the EER in real operation is not a constant value. It depends on the temperature difference between in- and outdoor. Typically, manufacturers provide data sheet EER values for an outdoor temperature of 35°C, an indoor temperature of 26.7°C and a humidity of 50% RH. If in-/outdoor temperatures deviate from these values the EER changes. For state-of-the-art R290 air-conditioning units EER values of 4.0 can be achieved for the above temperature combination.

4.2.2. Economic analysis

The economic comparison of the scenarios is based on the following parameters. Equation (1) shows the calculation of levelized cost of energy (LCOE), here applied to the cost of photovoltaic power generated.

$$LCOE=\frac{I_0+\sum_{t=1}^{n}\frac{C_{t,PV}}{(1+i)^t}}{\sum_{t=1}^{n}\frac{W_t}{(1+i)^t}} \tag{1}$$

I_0: total PV investment (CAPEX) cost [€]
$C_{t,PV}$: PV OPEX cost in the year t [€/a]
W_t: available PV energy in the year t [kWh_{el}/a]
i: interest rate [%/a]
n: expected lifetime of PV plant [a]

LCOE can be compared to the individual net electricity cost per country. If LCOE is greater than net electricity cost, PV power is more expensive and vice versa. Note that LCOE is calculated using cost figures only. Any earnings, e.g. from feed-in tariffs or other subsidies, are not taken into account for LCOE. Earnings have to be subtracted from LCOE in a separate calculation.

LCOE is an indicator for the economic potential of a PV array based on the electricity generated. It does not, however, provide information on how the PV power generated is being used for air-conditioning or grid feed-in per scenario and country. For this purpose, the net present value (NPV) of investment, operation and maintenance cost as well as any earnings for the PV array including AC unit has been calculated, eq. (2).

$$NPV=-I_0+\sum_{t=1}^{n}\frac{(E_{t,PV}-C_{t,PV+AC})}{(1+i)^t} \tag{2}$$

I_0: total PV investment (CAPEX) cost [€]
$E_{t,PV}$: PV earnings in the year t [€/a]
$C_{t,PV+AC}$: PV+AC OPEX cost in the year t [€/a]
i: interest rate [%/a]
n: expected lifetime of PV plant [a]

The total investment cost I_0 (CAPEX) was assumed to be additional, newly invested expenditure for the components of the PV plant and the AC unit in the scenarios. The focus was on the investigation of economic viability of an additional PV and AC plant to an existing building.

The annual PV+AC OPEX cost $C_{t,PV+AC}$ consists of:

- Remaining grid electricity cost for AC operation after subtracting PV self-consumption
- Operation and maintenance cost for PV array[9]

The annual PV earnings $E_{t,PV}$ consist of:

- Grid feed-in of excess PV energy (if a feed-in tariff is present)

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[9] AC OPEX cost has not been included here.

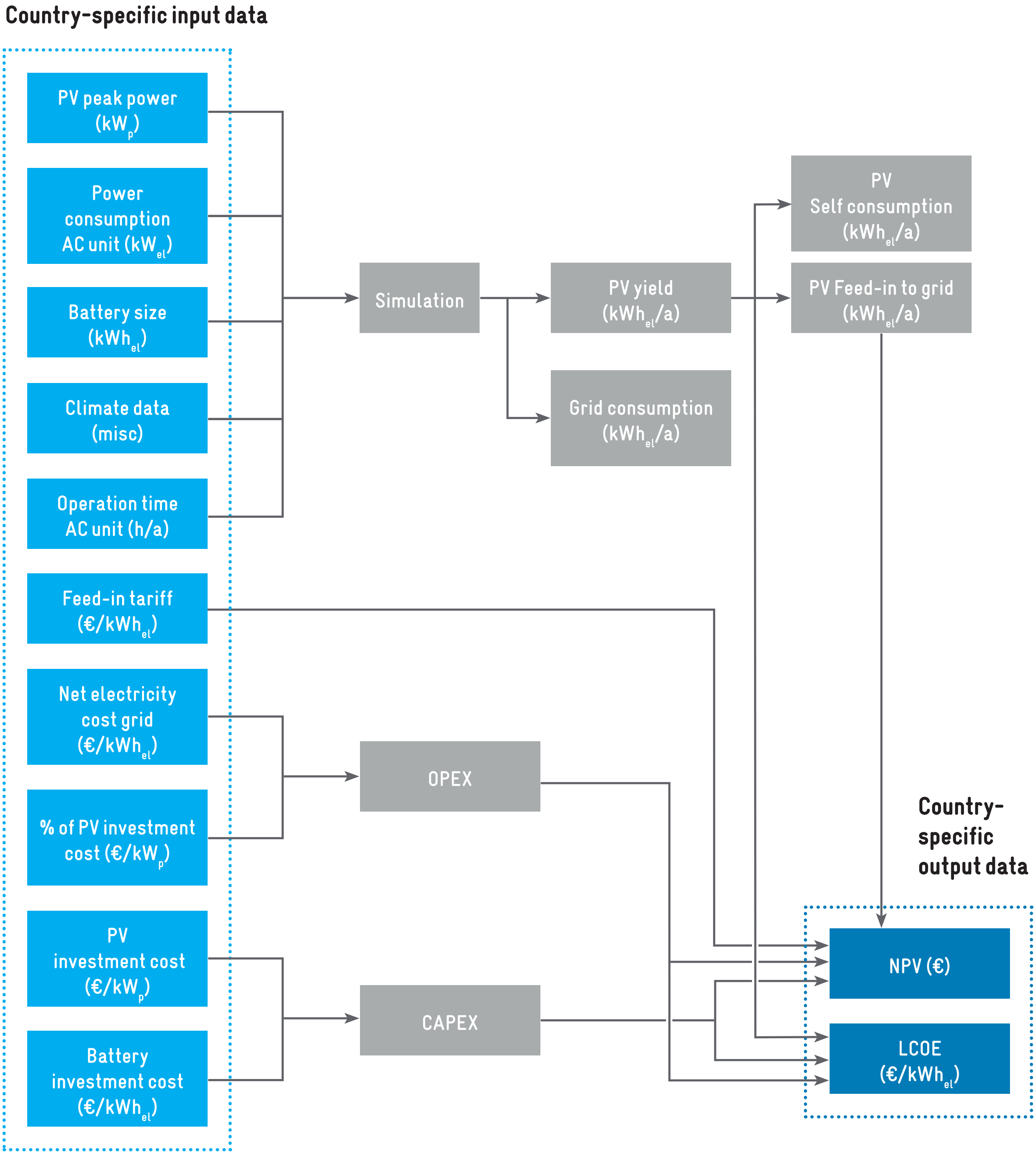

Figure 8: Input and output data of LCOE and NPV calculations. (Source: Solem Consulting)

4.3. Findings

Based on the assessment framework, results have been obtained for all scenarios and selected countries. Since some countries span over a large range of latitudes (e.g. China, India, Iran, etc.), three locations per country, defined by the lowest, average and highest solar irradiation within each country, are included. Low solar irradiation results in higher LCOE, high solar irradiation in lower LCOE.

4.3.1. Hybrid system – Residential house

Figure 9 shows the LCOE results for the grid connected system in a residential application, not accounting for any earnings from a feed-in tariff. In the residential case, a grid connected PV system with 1.0 kWp in an average solar location is able to generate electricity at lower than grid cost in China, Grenada, Honduras, India, Kenya, Philippines, Senegal, and Viet Nam. In Honduras and Thailand, lower than grid cost can only be achieved in good solar locations. In Colombia, Costa Rica, Ghana and Iran, PV-generated electricity is more expensive than grid power, regardless of the solar location.

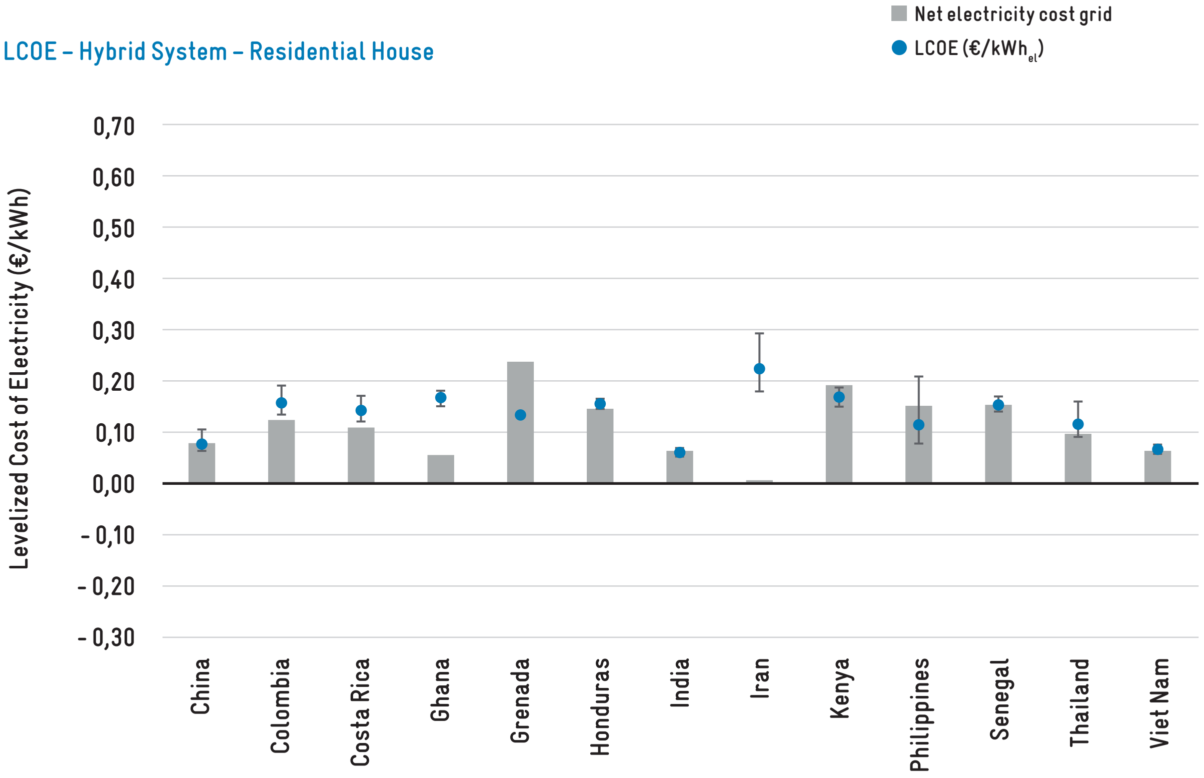

Figure 9: Levelized cost of electricity generated from PV system – Hybrid – Residential house. Blue dot equals a location with average solar irradiation, black bar equals locations with low (upper end of bar) and high (lower end of bar) solar irradiation. Gray column equals residential grid electricity cost.

Figure 10 shows the same LCOE cost as in *Figure 9*, however now including earnings from a residential feed-in tariff (FiT) subtracted, where present. See *Annex 8.3* for FiT details. It can be seen that the LCOE are influenced positively where a feed-in tariff is present, even to the extent that LCOE becomes a negative value. This means generating solar power at no cost and is the case in Grenada, Iran and Thailand. In Ghana, the FiT results in equal LCOE and grid cost, whereas in Costa Rica, Kenya and Senegal the FiT significantly decreases the LCOE below grid cost.

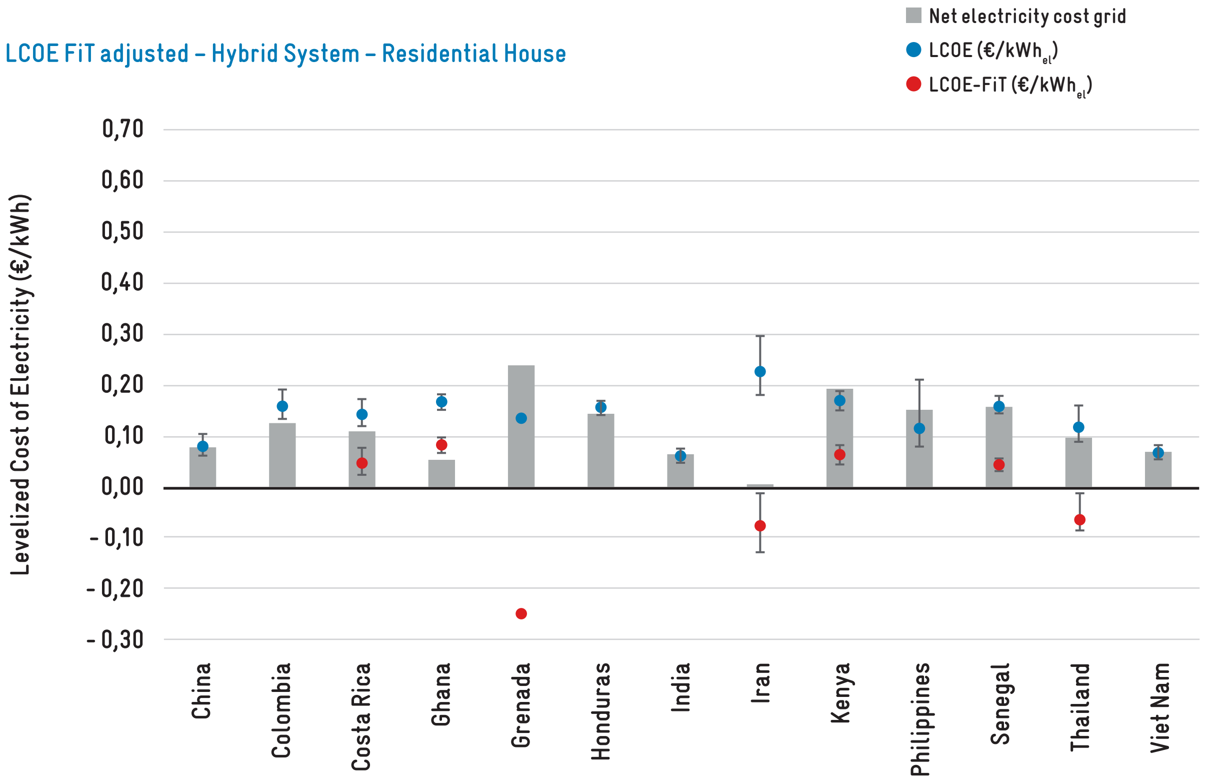

Figure 10: Levelized cost of electricity – Feed-in tariff adjusted – Hybrid – Residential house. Blue dot equals LCOE in a location with average solar irradiation, red dot equals LCOE minus FiT in a location with average solar irradiation. The black bar equals locations with low (upper end of bar) and high (lower end of bar) solar irradiation. Gray column equals residential grid electricity cost.

Figure 11 shows the net present value (NPV) for the residential size, grid connected system. Note that in all NPV calculations the FiT earnings are included. In most countries, the net present value is a net present cost (negative NPV value). This means that no revenue is generated from the PV system and grid consumption cost outweighs the self-consumption benefit of PV power generated. The exception here is Iran, where very low grid electricity cost combined with a rather high feed-in tariff results in a positive NPV for locations with high solar radiation. Compared to LCOE, the NPV gives more precise information on whether PV-powered green air-conditioning is economically feasible per country. In China, Costa Rica, Grenada, Honduras, Iran, Kenya, Senegal, Philippines and Thailand, the NPV cost of a PV-powered AC system is lower compared to the base case NPV cost. In Colombia, India and Vietnam the difference is negligible.

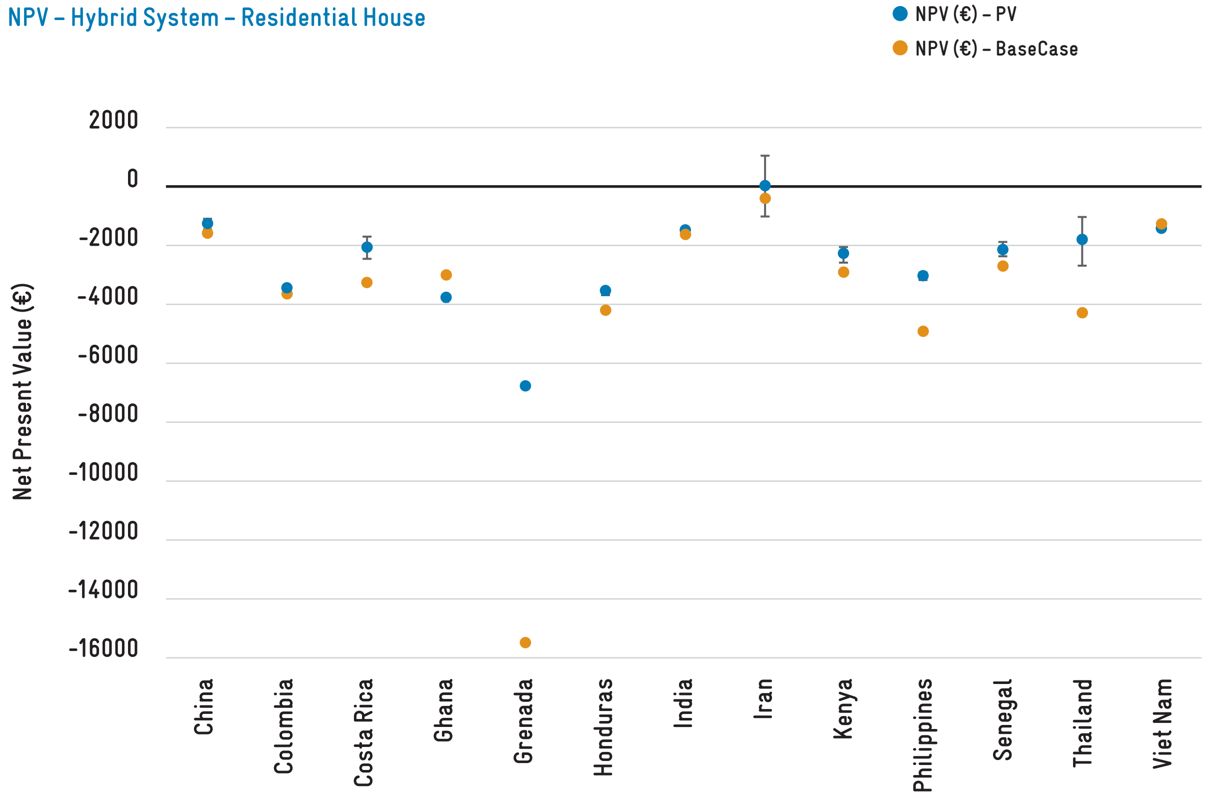

Figure 11: Net present value (NPV) – Hybrid – Residential house. Blue dot equals net present value for combined PV+AC system, grid connected. Orange dot represents net present value for the base case (100% grid-connected air-conditioning). Black bar equals locations with high (upper end of bar) and low (lower end of bar) solar irradiation.

4.3.2. Hybrid system – Commercial building

Figure 12 shows the LCOE for the grid connected system in a small commercial building. A small commercial size, grid connected PV system with 2.0 kW_p at an average solar location can generate electricity at lower than grid cost in China, Grenada, and India only. In all other countries included in this study, PV-generated electricity is more expensive than grid power, regardless of the solar location. Note that a FiT is not available for commercial buildings.

LCOE – Hybrid System – Commercial Building

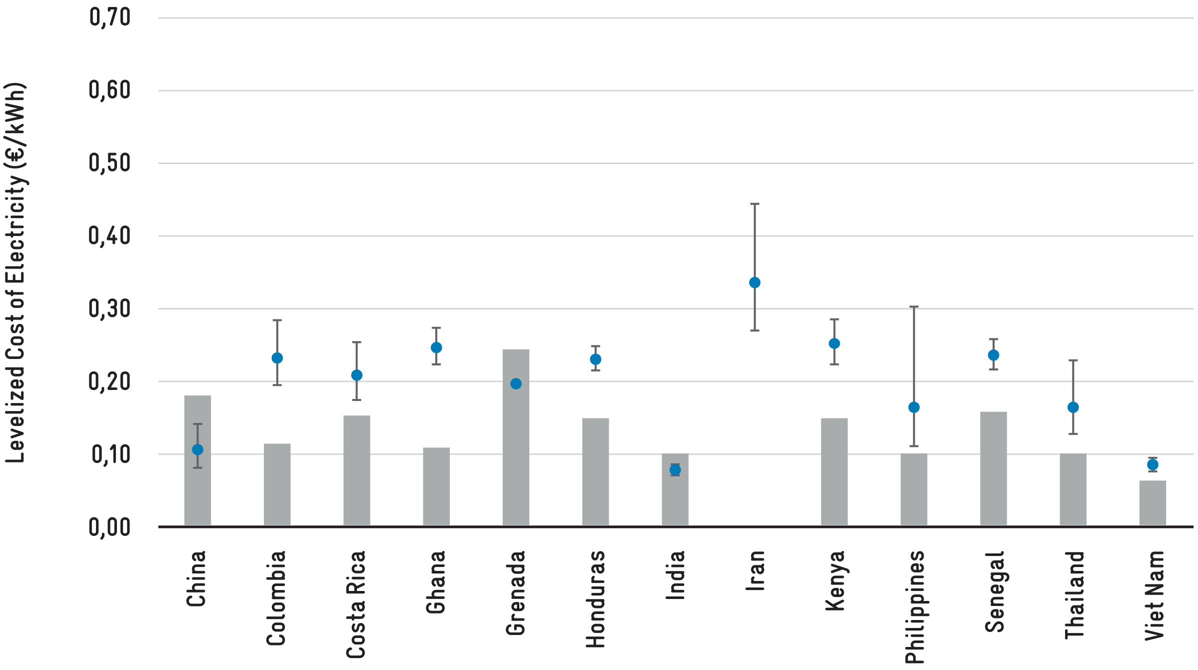

Figure 12: Levelized cost of electricity generated from PV system – On-Grid – Small commercial building. Blue dot equals a location with average solar irradiation, black bar equals locations with low (upper end of bar) and high (lower end of bar) solar irradiation. Gray column equals grid commercial electricity cost.

Figure 13 shows the net present value (NPV) for the commercial size, grid connected system. In all countries, the net present value is a net present cost (negative NPV value). This means that no revenue is generated from the PV system and grid consumption cost outweighs the self-consumption benefit of PV power generated. The NPV cost of a PV-based AC system is lower in China, Costa Rica, Grenada, Honduras, India, Kenya, Philippines, Thailand, Vietnam, as well as in average to good locations in Senegal.

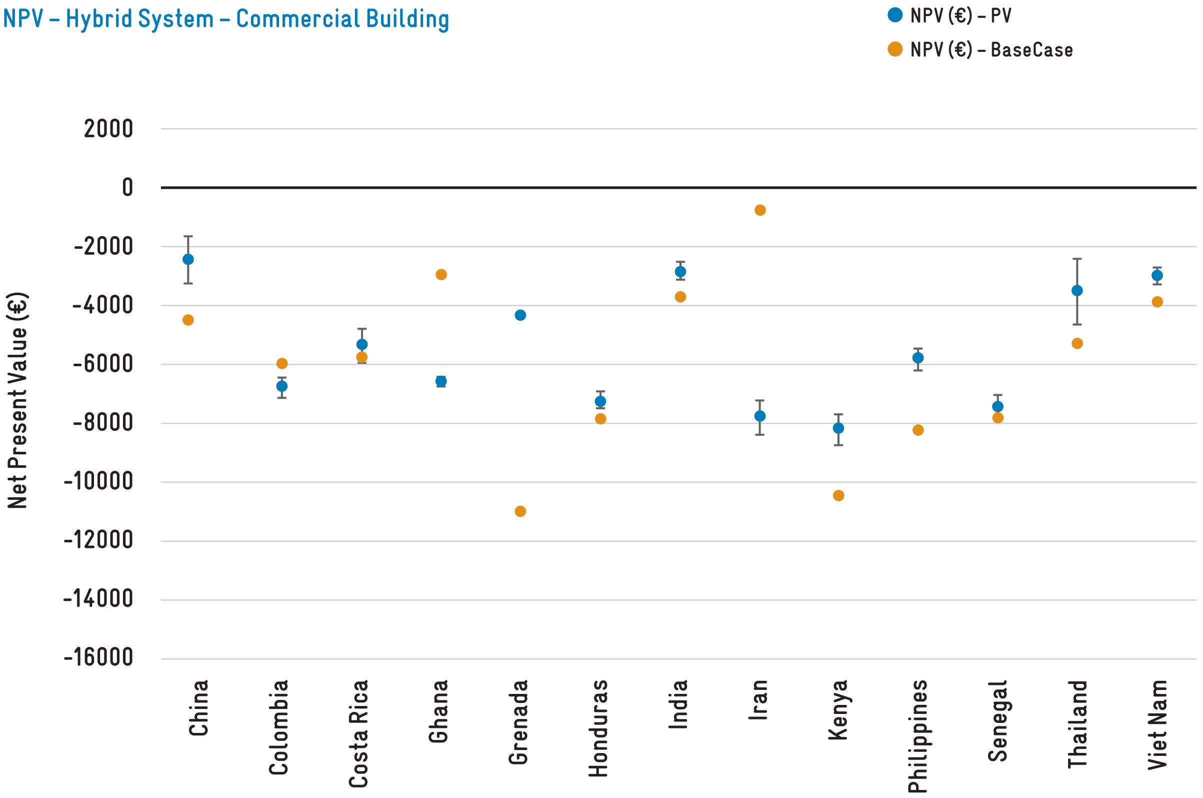

Figure 13: Net present value (NPV) – Hybrid – Small commercial building. Blue dot equals net present value for combined PV+AC system, grid connected. Orange dot represents net present value for the base case (100% grid-connected air-conditioning). Black bar equals locations with high (upper end of bar) and low (lower end of bar) solar irradiation.

4.3.3. Off-Grid system – Residential house

Figure 14 shows the LCOE for a residential size, grid connected PV system with 1.0 kW_p and a battery with 2.0 kWh_{el} capacity, not including FiT earnings. The additional cost for battery storage increases the LCOE in all countries. The benefit of additional self-consumption of PV generated power through battery storage only pays out in Grenada for all locations. In the Philippines, only average (blue dot) and good solar locations (lower end of bar) are economically viable. In all other countries, the LCOE for PV and battery operation is higher than grid electricity cost.

LCOE (€/kWh_{el}) – Off-Grid System – Residential house

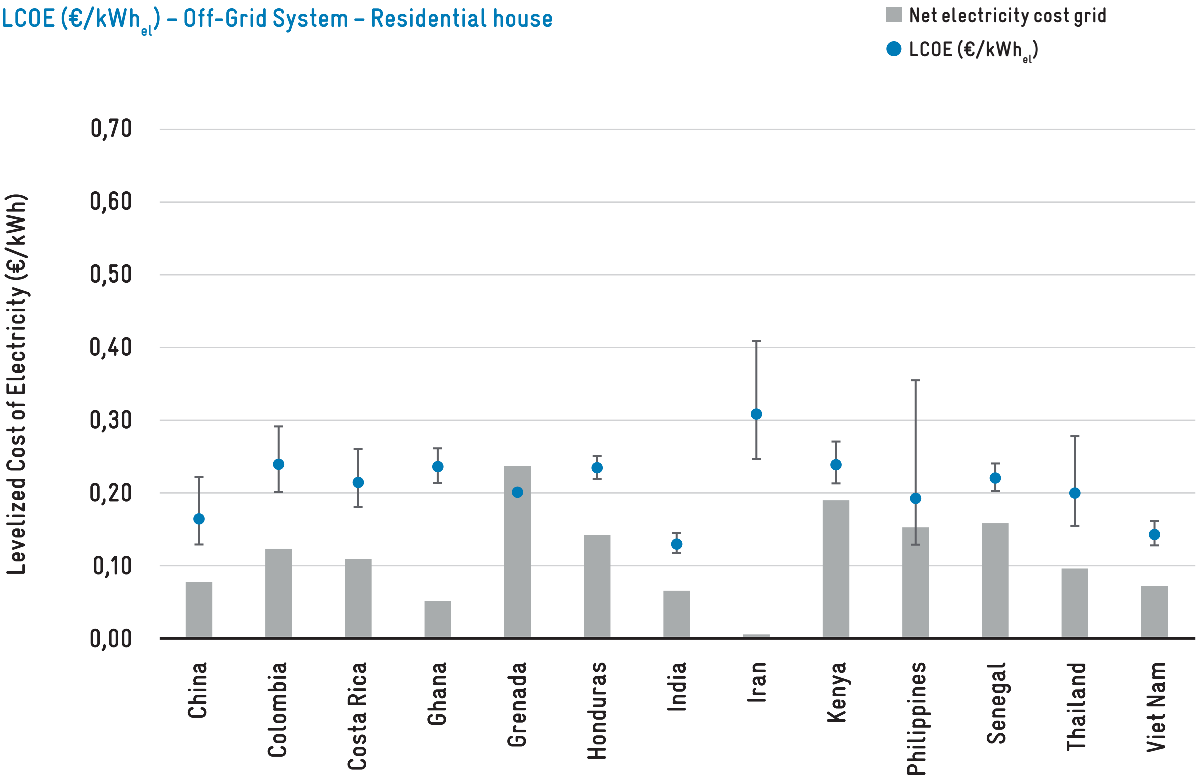

Figure 14: Levelized cost of electricity generated from PV system – Off-Grid – Residential house. Blue dot equals a location with average solar irradiation, black bar equals locations with low (upper end of bar) and high (lower end of bar) solar irradiation. Gray column equals residential grid electricity cost.

MAX
MIN

Figure 16 shows the NPV results including all cost and earnings from PV feed-in. It can be observed that Grenada, Philippines and Thailand have good economic potential for a residential off-grid system. In Costa Rica and Iran, PV+AC NPV values are within the range of the base case NPV, depending on the solar location. In all other countries, the net present cost for grid-powered air-conditioning is lower than for PV-powered air-conditioning.

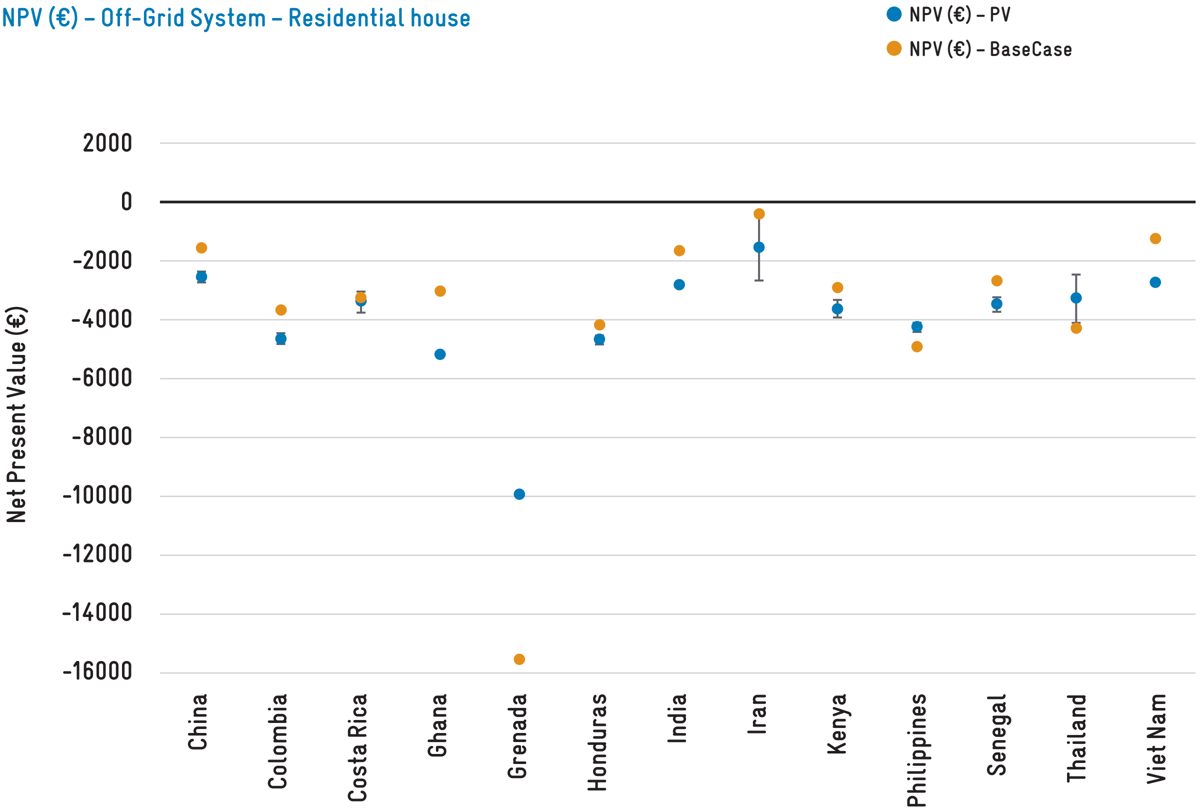

Figure 15: Net present value (NPV) – Off-Grid – Residential house. Blue dot equals net present value for combined PV+AC system, grid connected. Orange dot represents net present value for the base case (100% grid-connected air-conditioning). Black bar equals locations with high (upper end of bar) and low (lower end of bar) solar irradiation.

4.3.4. Off-Grid system – Commercial building

Figure 17 shows the LCOE results for a small commercial size, off-grid PV and battery system with 2.0 kWp and 2.5 kWhel of battery capacity. In most countries this off-grid system generates higher LCOE than grid electricity cost. The only exception are very good solar locations in China. Note that a FiT is not available for commercial buildings.

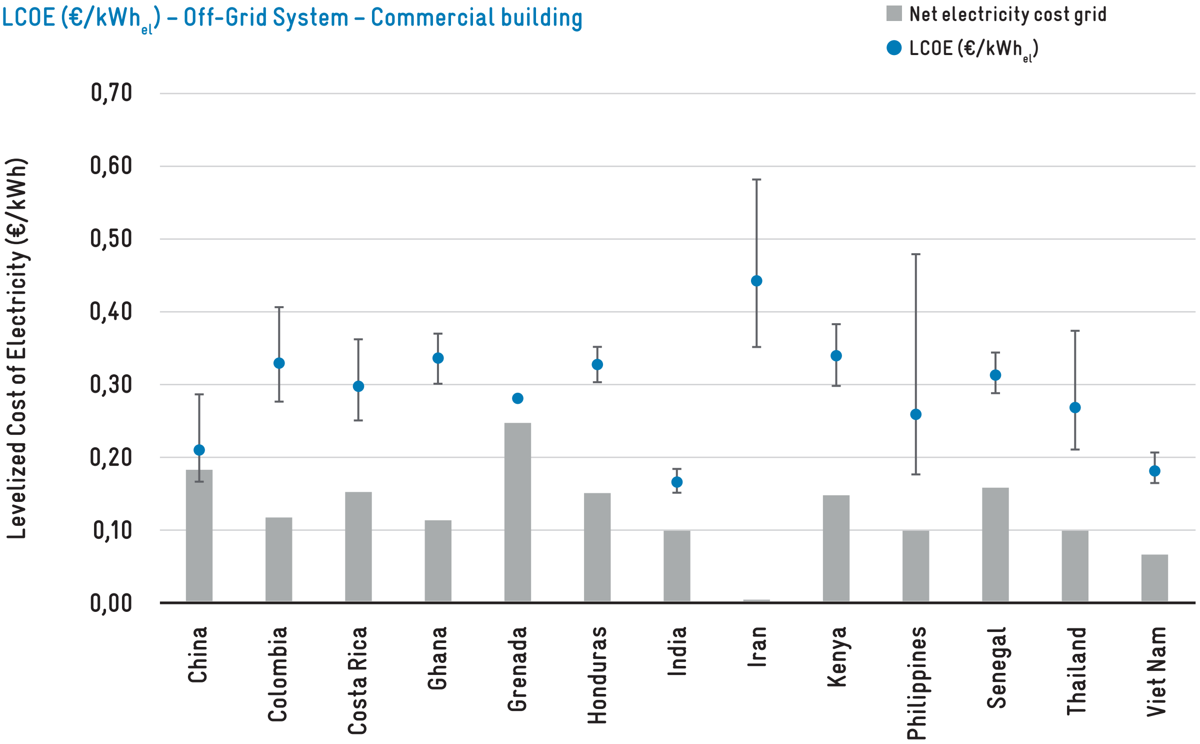

Figure 16: Levelized cost of electricity generated from PV system – Off-Grid – Small commercial building. Blue dot equals a location with average solar irradiation, black bar equals locations with low (upper end of bar) and high (lower end of bar) solar irradiation. Gray column equals grid commercial electricity cost.

Figure 18 provides the NPV results for the off-grid small commercial building scenario. All locations in Grenada and only locations with good solar irradiation in China, Philippines, and Kenya have lower net present cost than the base case. In Thailand, PV-NPV for good solar locations is within the range of the base case. In all other countries, the additional battery cost outweighs the benefit of increased self-consumption and the economics do not stack up.

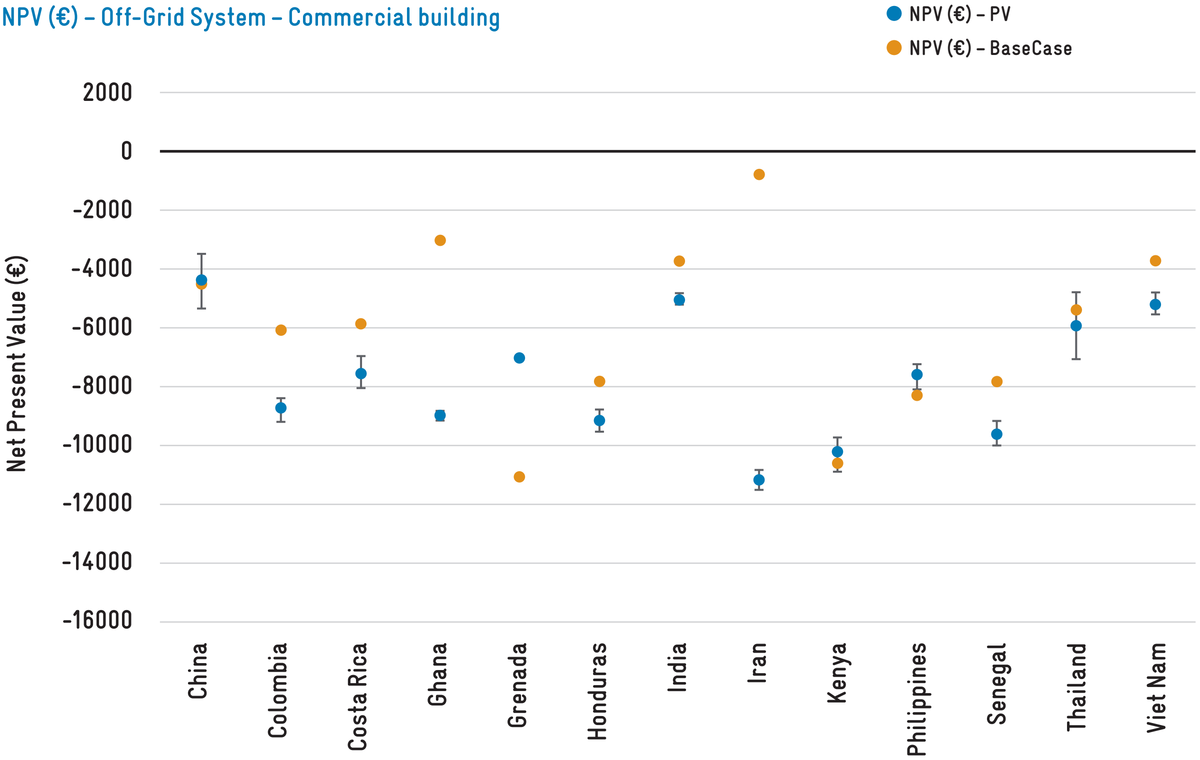

Figure 17: Net present value (NPV) – Off-Grid – Small commercial building. Blue dot equals net present value for combined PV+AC system, grid connected. Orange dot represents net present value for the base case (100% grid-connected air-conditioning). Black bar equals locations with high (upper end of bar) and low (lower end of bar) solar irradiation.

5. Case Study

In 2018, Médecins Sans Frontières (MSF) piloted the use of PV-powered split ACs at a hospital in Drouillard in Haiti. Air conditioning is one of the largest and growing fossil fuel consumers within MSF field operation, with an estimated fuel consumption at 35% of MSF's total fuel use and annual costs of three million euros. MSF's AC technologies comprise fixed-speed split ACs and increasingly variable-speed (inverter) split ACs, which are used to cool medical facilities such as operating theatres and laboratories, as well as for comfort cooling in offices and residences. The objective of the pilot project was to identify potential solar AC installations that could be used in MSF operations with the aim to reduce costs, increase autonomy as well as to reduce the carbon footprint of MSF's operations.

At Drouillard Hospital, MSF replaced five generator-powered fixed-speed split ACs with five PV-powered variable-speed split AC units of the same cooling capacity. Two of them have been connected to PV modules only ("PV AC"), one of them connected to PV modules and a diesel generator ("hybrid AC"), and two connected to PV-powered batteries ("PV AC with battery"). Similar to the conventional ACs, all newly installed ACs have a cooling capacity of 12000 btu/h and use R410a (GWP of 2088) as refrigerant. Each AC unit has been installed with eight PV panels with a nominal maximum power output of 275W each (intentionally oversized), summing up to 2.2kW. Later, this was altered to only 4 times 275W panels.

The equipment has been purchased internationally, two AC units from the Chinese manufacturer SuperEn, at a price below 1000 € each, and three AC units from the US company Hotspot Energy, at about double the price each. For the battery-backup case, a large lead-acid battery bank was available for use at the hospital, including 24 pieces of 2V battery cells with a total capacity of 1415 Ah (intentionally oversized to be discharged only to 80% for longevity reasons). Further battery types have not been considered in the scope of this project since the aim was to minimize reliance on batteries.

Three different use cases have been tested at Drouillard hospital. However, monitored energy performance data is only available for the daytime use case. For the hybrid and battery-backup cases, measurements are incomplete and uncertain, thus only estimated figures are included. In addition to the three tested installations with R410a split AC units, this study analyses the potential of using PV-powered Green ACs – defined as energy efficient split type ACs, using R290 as refrigerant (GWP of 1).

Use case	Type of room	Installation type
Daytime use	Consultation rooms (12 m²)	PV-powered AC off-grid
24-hour use	Operating theatre (42 m²)	PV-powered AC hybrid with diesel generator
Night-time use	Residential rooms (20 m²)	PV-powered AC off-grid with battery (lead-acid)

Table 7: Use cases of the MSF PV AC pilot project

5.1 Findings

Overall, the PV-powered AC systems were found to be suitable for MSF's operations as they performed very well, allowed to reduce cost and dependence on diesel generators, resulting in a lower climate impact, and co-benefits such as less noise pollution.

5.1.1 Technical performance

In terms of cooling supply, the PV-powered AC units without backup generated sufficient cooling for the two consultation rooms for daytime use (i.e. from around 8:00 in the morning until around 17:00 in the afternoon). The hybrid AC unit in the operating theatre also supplied most of the required cooling during the day and covered the remaining cooling needs using generator power. However, in larger buildings or rooms with less insulation, grid or generator power will likely be required during cloudy periods, in the evenings, nights, and early mornings. Many hybrid AC units connected to the generator might further present a challenge by creating high load peaks. A coping option, however, could be to install timers to better align AC operation with solar power output.

Similarly, the AC units with battery backup for night-time use performed reasonably well. However, it was found that large battery banks would be required to cover the cooling needs at night unless usage is very limited.

The table below indicates the energy consumption, as *monitored* by MSF for the daytime use case, as well as *estimated* figures for the hybrid and battery-backup use cases. It should be noted that the installations belong to different rooms and use cases, as listed in *Table 8*, which makes comparison between them unapplicable. The yearly energy consumption estimates are used for the cost and climate impact estimations in the following two sections.

Installation type	Estimated energy consumption/year (kWh)	Average energy consumption/day (kWh)	Highest energy consumption/day (kWh)	Lowest energy consumption/day (kWh)
Fixed-speed AC with generator (daytime, average delta-T = 5.3° C)	1680	4.6	6.0	3.4
PV AC (daytime, average delta-T = 5.9° C)	690	1.9	2.5	1.2
Hybrid AC (24-hours)	Fixed-speed AC: 3500 (1.2kW, 8 hours/day) PV AC: 1600 (total) Max. PV power: 2600	n/a	n/a	n/a
			n/a	n/a
PV AC with battery	3175.5 (delta-T = 10° C)	8.7 (delta-T = 10° C)	n/a	n/a
	1825 (delta-T = 5° C)	5 (delta-T = 5° C)		

Table 8: Energy consumption (green = monitored, yellow = estimated) for different installation types (MSF, 2020)

5.1.2 Cost

The higher energy efficiency of variable-speed split ACs (compared to fixed-speed split ACs) as well as the (partial) replacement of generator power with solar power allowed to reduce the cost of air conditioning significantly. For instance, the potential savings for a 12 m^2 room in a well-insulated building and in Haiti's climate is estimated to be in the order of 1,500 kWh/year compared to a fixed-speed generator-powered AC. This can be achieved with four 275 W PV panels. The savings with the Drouillard generators and Haiti diesel prices is thus around 450 EUR/year (0.3 litres/kWh and 0.89 EUR/litre of diesel currently), which is now in the order of the total cost for the PV panels – excluding installation. At the time of the pilot project, the price of the PV panels was nearly twice as high. It should also be noted that the Haiti diesel prices are (or at least were) very low.

In the 24-hours use case, the savings with a hybrid PV-powered AC compared to a fixed-speed AC can be much higher, though cost figures cannot be provided due to the lack of reliable data on generator vs. solar PV power supply. Nevertheless, the estimated 2600 kWh per year PV power supply serve as an indication of the maximum generator power that can be saved, which translates into 694 EUR savings annually.

In the battery-backup case, cost are significantly higher due to the battery investment and replacement cost (here: lead-acid batteries). With a yearly battery replacement cost of around 1000 EUR per AC unit, the annual cost of generator-powered fixedspeed AC are well below. However, higher diesel prices and high temperature differences would decrease the cost difference, thus the battery-backup system will primarily be interesting for very remote projects. In MSF, this was not recommended for further implementation at the time of the pilot project.

Moreover, the fuel cost for air conditioning were found to be linearly dependent on the *delta-T*. The cost for a 10° C difference is nearly twice as high as for 5° C. Therefore, there is a huge savings potential by reducing the temperature difference between indoor and outdoor.

Daytime use	Generator-powered fixed-speed AC	PV-powered AC off-grid	PV-powered Green AC[11] hybrid with generator
One-off investment (EUR)[12]	0	1100	1100
Annual cost (EUR)	450	0	0

24-hours use	Generator-powered fixed-speed AC	PV-powered AC hybrid with generator	PV-powered Green AC[11] off-grid
One-off investment (EUR)[12]	0	1100	1100
Annual cost (EUR)	935	n/a	n/a

Night-time use	Generator-powered fixed-speed AC	PV-powered AC off-grid with battery	PV-powered Green AC[11] off-grid with battery
One-off investment (EUR)[12]	0	2100 – 3100	2100 – 3100
Annual cost (EUR)[12], delta-T = 10° C	850	1000	1000
Annual cost (EUR)[12], delta-T = 5° C	490	1000	1000

Table 9: Approximated cost in different scenarios

[11] PV-powered off-grid R290 Split AC

[12] Approximated cost, excluding AC and installation cost. Installation was done by MSF staff.

5.1.3 Climate impact

The GHG emissions included in the climate impact assessment comprise direct emissions from refrigerant leakage and indirect emissions from generator electricity consumption. The calculations do not account for embodied carbon emissions in all life-cycle phases due to the lack of comparable data for all scenarios. For instance, the embedded GHG emissions from li-ion battery manufacturing are estimated between 39 kg CO_2eq/kWh and 196 kg CO_2 eq/kWh, depending on the methodology (Cerdas, Andrew, Thiede & Herrmann, 2018). For a battery with 2.83 kWh capacity, this means additional 110 to 550 kg CO_2 eq (per battery lifetime). The full list of assumptions can be found in the appendix 8.4.

Daytime use	Generator-powered fixed-speed AC	PV-powered AC off-grid	PV-powered Green AC[11] off-grid
Total direct GHG emissions (lifetime) (kg CO_2 eq)	5232.8	5232.8	2.6
Total indirect GHG emissions (lifetime) (kg CO_2 eq)	18900	0	0
Total annual GHG emission savings (kg CO_2 eq/a)	Base case	1260	1608.7

24-hours use[13]	Generator-powered fixed-speed AC	PV-powered AC hybrid with generator	PV-powered Green AC hybrid with generator
Total direct GHG emissions (lifetime) (kg CO_2 eq)	5232.8	5232.8	2.6
Total indirect GHG emissions (lifetime) (kg CO_2 eq)	42052	n/a	n/a
Total annual GHG emission savings (kg CO_2 eq/a)	Base case	n/a	n/a

Night-time use[13]	Generator-powered fixed-speed AC	PV-powered AC off-grid with battery	PV-powered Green AC off-grid with battery
Total direct GHG emissions (lifetime) (kg CO_2 eq)	5232.8	5232.8	2.6
Total indirect GHG emissions (lifetime) (kg CO_2 eq)	35724.4	0	0
Total annual GHG emission savings (kg CO_2 eq/a)	Base case	2382	2730.3

Table 10: Estimated GHG emissions in different scenarios

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[13] Based on estimated figures (see table 8), not observed.

5.2 Lessons learned

MSF's project in Haiti showcased the high potential of the use of PV-powered AC systems for cooling off-grid social infrastructure – offering reduced dependency on generator power, significant cost reductions, and a lower climate impact of air conditioning. Following the promising pilot study results, up until now, MSF has installed more than 150 solar AC units in Malawi, South Sudan, Bangladesh, and other countries, and is conducting more in-depth analyses of their energy performance. The focus is on hybrid AC units to avoid the need for batteries.

To support project developers, MSF and Arup developed a sizing tool, which provides a high-level feasibility assessment for the installation of solar powered AC[14]. The tool allows to evaluate the size of a PV-powered AC system to meet given cooling needs (daytime use only), and to compare cost and environmental impact to conventional AC systems powered by diesel generators.

However, several barriers remain with regards to larger scale uptake of the technology, including challenges to deliver solar AC solutions to remote areas, a limited number of suppliers, lack of awareness among end-users, and higher upfront cost compared to generator-powered solutions. Yet, the PV-powered AC systems are a "clear cut" application, which can be installed first and converted to a larger system later. Ultimately, PV-powered ACs are only one piece in the transition to renewable energy sources and energy efficiency.

Lastly, the best solution from a climate impact perspective is not using air conditioners at all or reduce it as much as operationally possible. This includes reducing the required temperature difference between indoor and outdoor as well as timing the AC operation in line with solar power output. Moreover, good insulation of buildings, as in the case of Drouillard hospital, and other passive cooling measures are key for reducing the cooling needs.

[14] https://solar-ac.arup.com/landing-page

6. Conclusions and recommendations

This study explores market trends of PV AC systems, examines the technical and economic potential of solar PV-powered green air conditioners using dynamic economic modelling, and provides a case study of a solar AC pilot project from Médecins Sans Frontières in Haiti. The dynamic economic analysis includes four different technical solutions for thirteen different countries using three different locations per country. All PV AC scenarios have further been compared against a base-case scenario using conventional AC units and 100% grid electricity supply. The technical solutions investigated per country include:

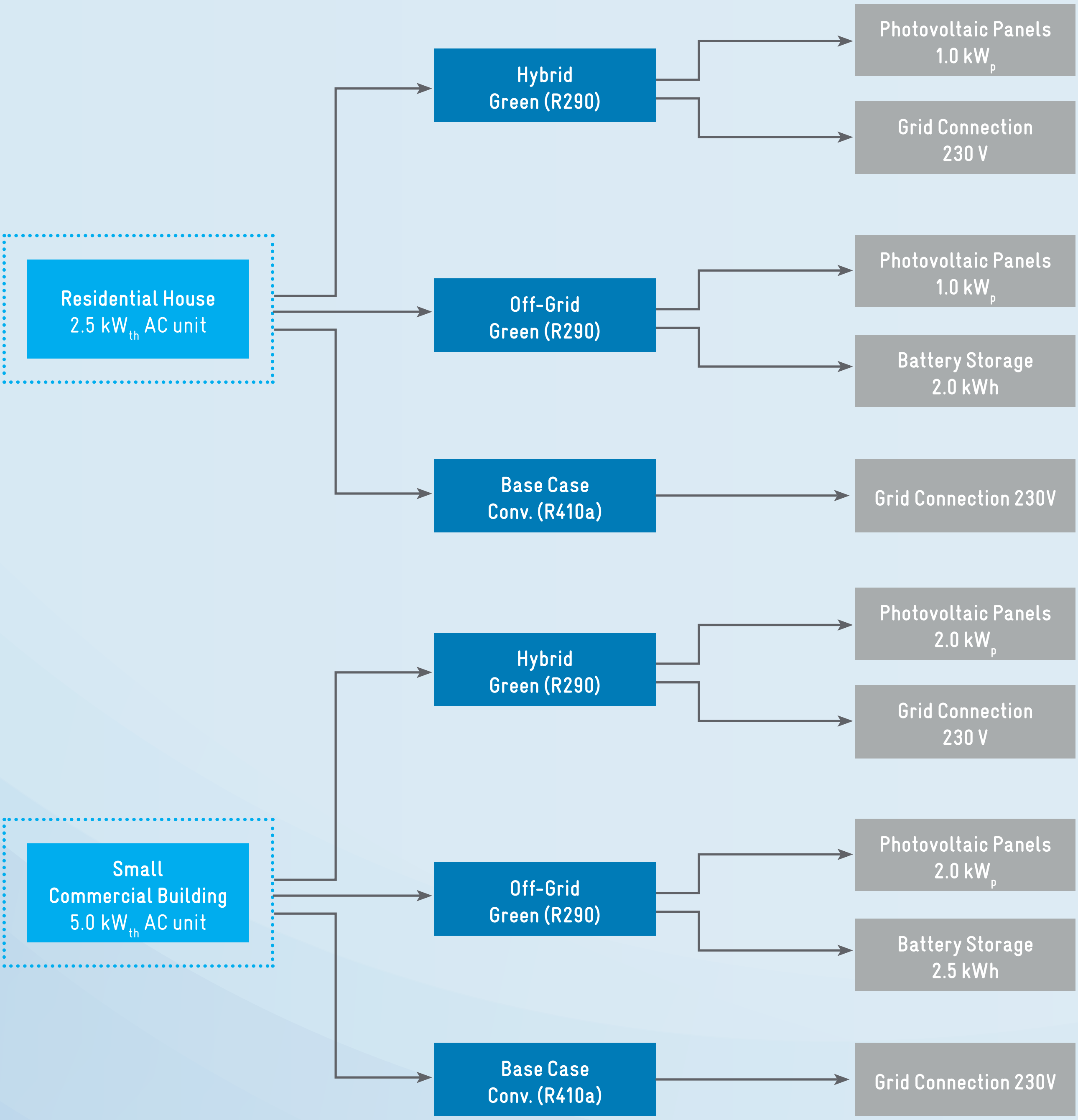

Figure 18: Overview of technical solutions investigated. Top: residential house; bottom: small commercial building.

The four different solar-based solutions shown in *Figure 19* have been investigated for three different locations in each country, namely minimum, average and maximum annual global solar irradiation on the horizontal. Applied to thirteen countries this yields a total of 156 different combinations, which have been individually calculated using a dynamic simulation software package. Results from these simulations have been used in dynamic economic calculations of Levelized Cost of Electricity and Net Present Value. *Table 11* shows an overview of scenarios and countries, indicating where solar-based AC has a financial advantage over 100% grid-supplied AC.

- **Hybrid PV-powered air-conditioning** for a residential house has a financial advantage over grid-based air-conditioning in eleven out of thirteen countries investigated. Exceptions are Ghana and Vietnam.
- **Off-grid PV-powered air-conditioning** for residential houses is feasible in five out of thirteen countries, namely Costa Rica, Iran, Grenada, Philippines, and Thailand.
- **Hybrid PV-powered air-conditioning** for a small commercial building has a financial advantage over grid-based air-conditioning in ten of the countries investigated, except for Colombia, Ghana, and Iran.
- **Off-grid PV-powered air-conditioning** for a small commercial building is only feasible in China, Grenada, Kenya, and Philippines.

	Resisential Hybrid	Residential Off-Grid	Commecial Hybrid	Commercial Off-Grid
China	+		++	+
Colombia	+			
Costa Rica	++	+	+	
Ghana				
Grenada	++	++	++	++
Hunduras	++		++	
India	+		++	
Iran	+	+		
Kenya	++		++	+
Phillippines	++	++	++	+
Senegal	+		+	
Thailand	++	++	++	
Vietnam			++	

Table 11: Comparison of economic potential for solar PV AC per country and scenario

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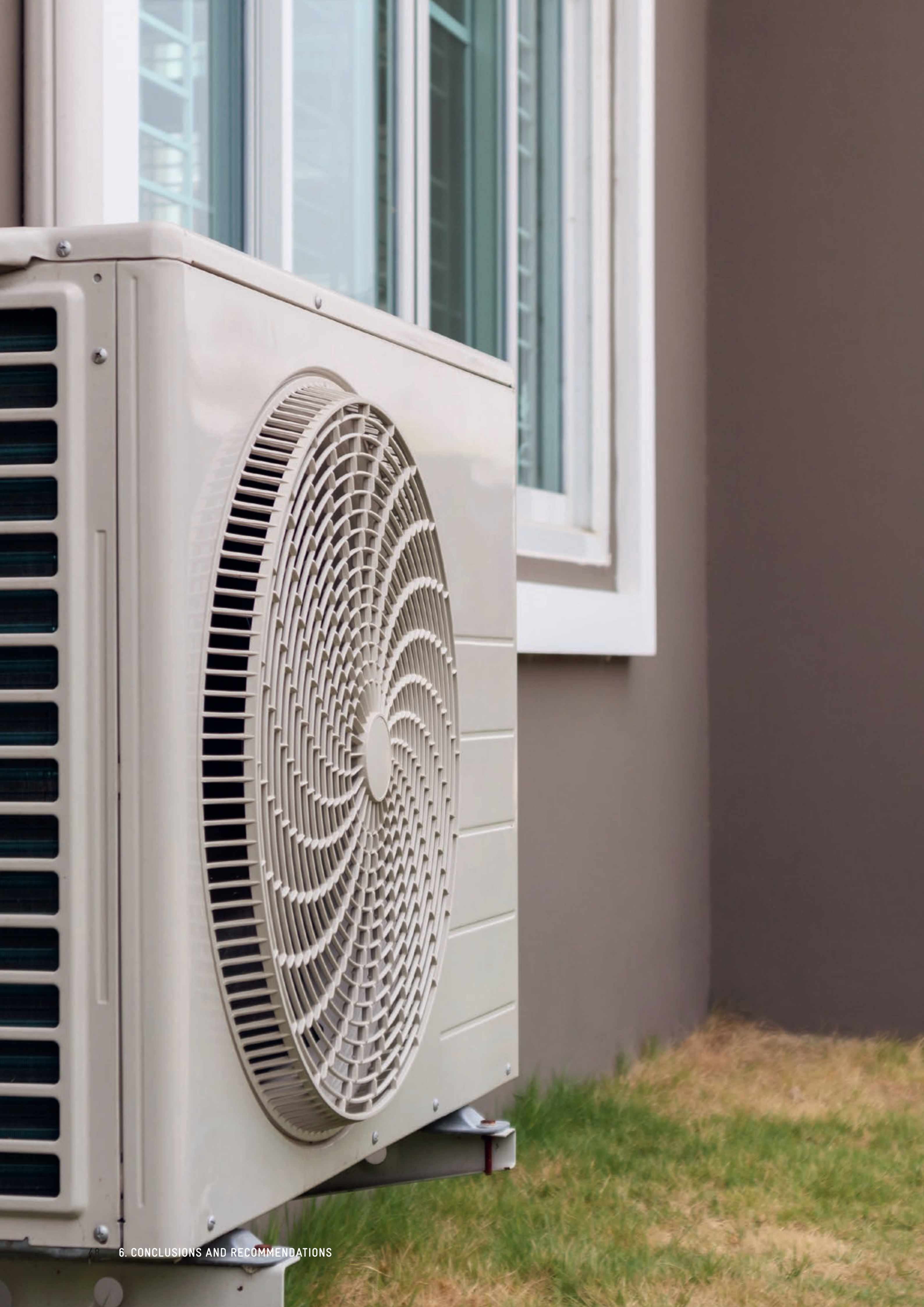
[15] ++ : Net Present Value (NPV) of the solar scenario is higher than of the base case scenario.
\+ : NPV of the solar scenario is within sensitivity range of the base case scenario.



The analysis shows that solar radiation, AC operating times (daytime use), equipment (investment) costs, grid electricity costs (or diesel costs where generators are used) and a feed-in-tariff are key factors influencing the economic feasibility of PV-powered AC systems. The hybrid solution shows a greater potential compared to the off-grid system in both residential and commercial applications. It should be noted that due to the uncertainty attached to the data and modelling assumptions the results of this study serve as indications and a starting point for further research and practical experience.

Main barriers include the limited local availability of key components in many partner countries, especially when it comes to efficient split ACs using R290 refrigerant (Green ACs) as well as suitable and affordable battery technology. Importing these key components comes with higher investment costs but can result in lower total costs in the long term, if the above-mentioned key factors sufficiently apply. It is expected that with the growing battery market for decentralized residential and commercial RE electricity storage, battery costs will continue to fall and thereby increase the economic attractiveness of off-grid PV AC solutions.

When choosing the battery technology, it is advised to carefully evaluate features like lifetime, efficiency, product safety, and environmental performance.

To enhance framework conditions for PV-powered Green ACs it is recommended to (1) establish a feed-in-tariff and net metering scheme, where unavailable, (2) strengthen supply chains for Green ACs, complete solar AC solutions and suitable battery technologies, including recycling infrastructure for all technical components, and (3) provide trainings for technicians in the cooling and solar PV sectors regarding installation and servicing of complete PV-powered AC solutions.

Finally, by highlighting the potential of PV-powered AC systems in terms of economic feasibility as well as climate benefits, this study aimed to contribute to increased awareness and demand, which are key factors to enable reinforcing feedback mechanisms driving the diffusion of PV-powered AC systems globally.

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8. Annexes

8.1. Air-conditioning load data

8.1.1. Residential AC load pattern

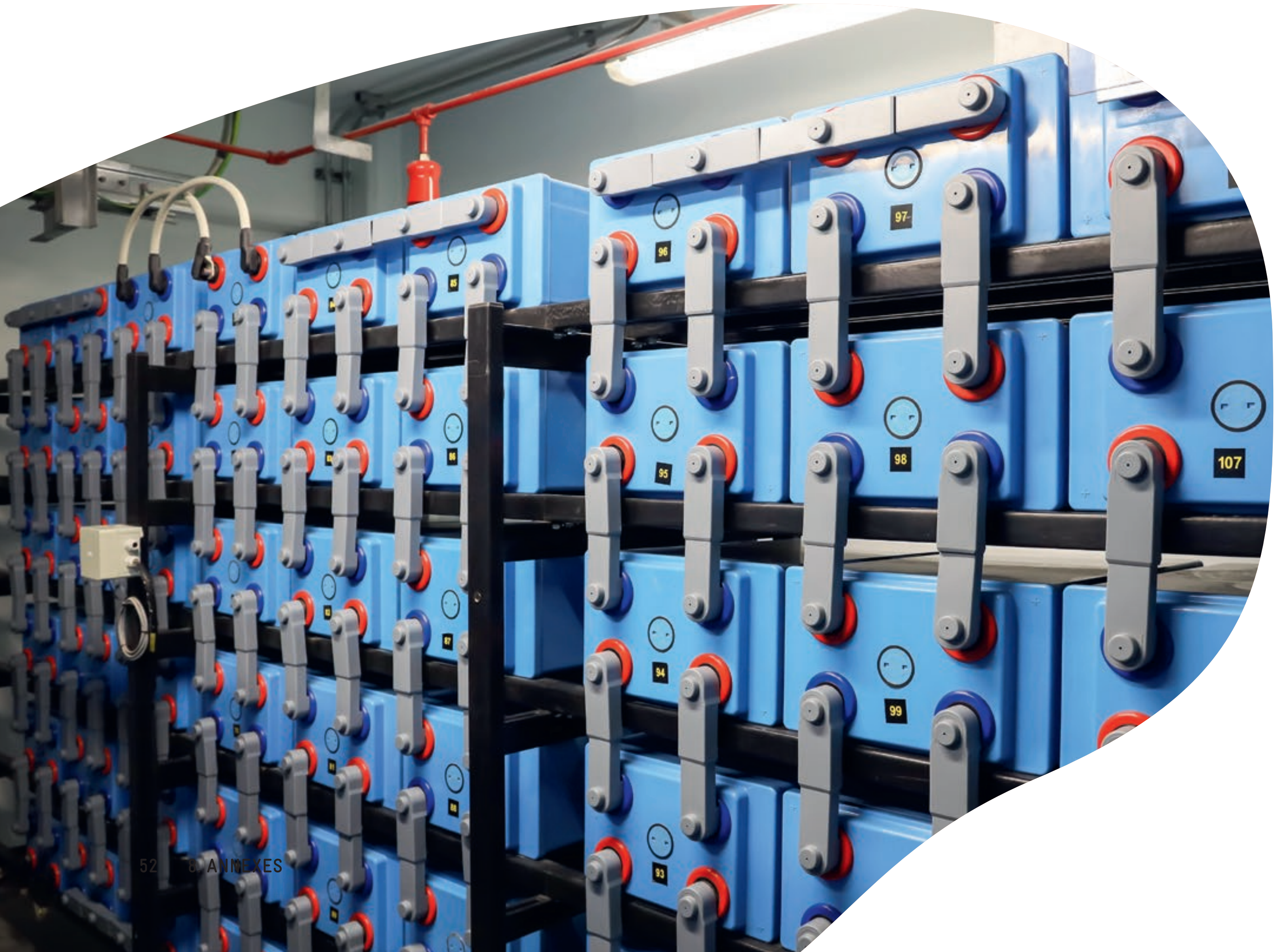
Scenario	Country	AC thermal load of building (kWhth/a)	AC operating times
Residential (625 W electrical power of AC unit)	Grenada	4,000	7am-8pm (Mo-Fri, Sun), 7-9pm (Sat), January to December
	Ghana	3,040	8am-6pm (Mo-Sun), January to December
	India	1,250	10am-5pm (Mo-Sun), April to October
	Philippines	1,830	9am-5pm (Mo-Sun), mid-February to mid-November
	Thailand	2,430	9am-5pm (Mo-Sun), January to December
	Iran, Kenia, Viet Nam	725	10am-5pm (Mo-Sun), mid-May to mid-September
	Colombia, Costa Rica, Honduras	1,600	10am-5pm (Mo-Sun), mid-February to mid-November
	China, Senegal	930	10am-5pm (Mon-Fri), 10am-6pm (Sat/Sun), May to September
Commercial (1250 W electrical power of AC unit)	Colombia, Grenada, Ghana, Senegal	3,000	9am-6pm (Mo-Fri), mid-February to November
	Viet Nam, Thailand, Philippines, Kenia, Iran, India, Honduras, Cost Rica, China	3,255	9am-6pm (Mo-Fri), February to November

8.2. Investment cost data

8.2.1. Battery cost (installed, incl. VAT)

LiFePO4 lithium-ion batteries are offered commercially over a wide range of prices. A global average value of € 400/$\mathrm{kWh_{el}}$ was chosen for all battery cost in order to simplify the assumptions. The additional cost for the battery inverter and charge controller was assumed to be 20% of the battery investment cost.

Specific battery cost (€/$\mathrm{kWh_{el}}$)	Source
234	https://winston-battery.en.made-in-china.com/product/a0EfjsmuvHYT/China-Solar-Prismatic-3-2V-304ah-LiFePO4-Lithium-Ion-Battery.html
533	https://www.amazon.de/dp/B084DB36KW
700	https://www.amazon.com/gp/product/B06XX197GJ
1051	https://www.solarchoice.net.au/blog/battery-storage-price
400	GLOBAL AVERAGE VALUE chosen for this study



8.2.2. PV system cost (installed, incl. VAT)

The investment cost for PV systems excluding battery storage has been taken from the table below, using country-specific values for the calculations.

Country	Specific investment cost PV system installed, incl. VAT	References Note that cost figures in this table do not include battery cost.
	€/kW_p	
China	660	https://irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf
Colombia	1947	https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_Global_Renewables_Outlook_2020.pdf; https://www.vivasolar-colombia.com/productos/paquetes-completos/
Costa Rica	1982	https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_Global_Renewables_Outlook_2020.pdf; https://crsolarsolutions.com/the-myths-of-solar-installation-costs-in-costa-rica/
Ghana	2442	https://htcghana.com/solar-panels-for-homes-in-ghana/; http://www.aaainfrastructure.com/ghana-rooftop-solar.html
Grenada	1982	https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_Global_Renewables_Outlook_2020.pdf; no specific cost found, assumed same cost as Costa Rica (US influenced cost)
Honduras	2022	https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_Global_Renewables_Outlook_2020.pdf; https://suelosolar.com/tienda/articulo_amp.asp?id=1217
India	582	https://irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf
Iran	2836	https://www.tehrantimes.com/news/465701/Iranian-households-install-4-500-rooftop-PV-stations
Kenya	2465	https://powerafricasolar.com/project/cost-of-solar-in-kenya-solar-panel-cost-in-kenya-cost-of-solar-installation-in-kenya; https://solarshop.co.ke
Philippines	1352	https://solaric.com.ph/blog/cost-solar-panels-2019/; 2019 average 51 PHP/USD, https://www.solarrooftops.ph
Senegal	2700	https://nrjsolaires.com/collections/kit-solaire
Thailand	1227	https://eyekandi-solar.com/how-a-solar-grid-tied-system-works
Viet Nam	602	https://vietnaminsider.vn/rooftop-solar-panels-installation-booms-in-vietnam
Global average	768	https://www.statista.com/statistics/809796/global-solar-power-installation-cost-per-kilowatt; https://www.pvxchange.com/price-index

8.3 LCOE data including feed-in tariff earnings - Residential house

	Hybrid system – Residential house			Off Grid system – Residential house		
	LCOE (average solar location)	FiT	LCOE – FiT	LCOE (average solar location)	FiT	LCOE – FiT
Country	€/kWh$_{el}$	€/kWh$_{el}$	€/kWh$_{el}$	€/kWh$_{el}$	€/kWh$_{el}$	€/kWh$_{el}$
China	0.045	–	0.045	0.107	–	0.107
Colombia	0.126	–	0.126	0.185	–	0.185
Costa Rica	0.114	0.0952	0.019	0.166	0.0952	0.071
Ghana	0.138	0.086	0.052	0.189	0.086	0.103
Grenada	0.108	0.3966	−0.289	0.156	0.3966	−0.240
Honduras	0.127	–	0.127	0.183	–	0.183
India	0.033	–	0.033	0.084	–	0.084
Iran	0.191	0.3037	−0.112	0.252	0.3037	−0.051
Kenya	0.141	0.1056	0.035	0.192	0.1056	0.086
Philippines	0.084	–	0.084	0.141	–	0.141
Senegal	0.134	0.114	0.020	0.179	0.114	0.065
Thailand	0.083	0.183	−0.100	0.144	0.183	−0.039
Viet Nam	0.037	–	0.037	0.093	–	0.093

8.4 Case Study – Climate impact assessment assumptions

Lifetime of ACs	15 years
Refrigerant charge size R410a AC	1 kg
Refrigerant charge size R290 AC	0.38 kg
GWP of R410a	2256
GWP of R290	3
Refrigerant leakage rates	• Initial: 2% • Annual operation: 10% • End of life: 80%
SEER (W/W)	• Fixed-speed AC (R410a): 2.93 • Variable-speed AC (R410a): 6.45 • Variable-speed AC (R290): 8.5
Cooling capacity	12,000 btu/h
Diesel consumption (generator)	0.3 l/kWh
Diesel generator emissions factor	2.67 kg CO_2eq/l
Diesel price	0.89 EUR/l

The GHG emissions only include direct emissions from refrigerant leakage and indirect emissions from generator electricity consumption.
The calculations do not account for embodied carbon emissions in all life-cycle phases due to the lack of comparable data for all scenarios.

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