IRENA
International Renewable Energy Agency

SOLAR SIMULATORS:

Application to Developing Cities

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CONTENTS

FIGURES

ABBREVIATIONS

3D	three-dimensional
cm	centimetre
DEM	digital elevation model
DHI	diffuse horizontal irradiation
DNI	direct normal irradiation
DTI	direct tilted irradiation
GHI	global horizontal irradiance
GIS	geographic information system
GTI	global tilted irradiance
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LAI	leaf area index
LCOE	levelised cost of electricity
LiDAR	light detection and ranging
PV	photovoltaic
S	shadowing effect
t	time

EXECUTIVE SUMMARY

Over half the world's population, or 3.5 billion people, are now living in cities. By 2050 this number is expected to reach nearly 6.5 billion. Cities, moreover, already account for 60-80% of global energy consumption, while urban energy supply systems face increasing pressure.

Typical challenges range from ageing infrastructure and high consumer prices, mainly in developed cities, to efficiency and reliability issues, typically seen in the cities of developing countries.

At the same time, the energy supply landscape globally is experiencing rapid change made possible by cutting-edge innovation. Storage technologies are improving and electrical loads are more efficient. Mini-grid applications are better understood and direct end uses such as heating, cooling and transport are being electrified. In addition, the cost of technologies that exploit alternative energy sources, notably solar photovoltaic (PV) systems, is continuing to decline.

With the right policies and sound urban planning practices at city level, administrators are particularly well positioned to effectively use these developments to manage energy demand, while simultaneously securing energy supply for their constituents that is clean, affordable and reliable both today and in the future. Urban planning and policy design, however, are complex. They require astute attention to the local conditions of the city – the structure of the local economy, income levels, existing regulations and overarching fiscal policies. They may also require attention to the priorities of central government and potential market players, including the private sector.

In advanced economies such as France, the Netherlands, the Republic of Korea and the United States, solar PV rooftop simulators have been put to effective use to aid the assessment of conditions in specific cities, with the prospect of establishing rooftop PV markets. These simulators use cutting-edge technology that combines know-how in remote sensing, high-performance data processing, three-dimensional (3D) building footprint generation and solar irradiation modelling.

This study explores the possibility of deploying similar simulation engines inexpensively, but effectively, in developing cities. If deployed correctly, they can quicken the pace of energy planning and improve the efficiency of policy structures aimed at creating sustainable markets for rooftop solar PV in these parts of the world. They can also provide important metrics for individual businesses and homeowners to assess PV systems as an electricity supply option for their properties.

The study elaborates the evolution of solar PV simulators, accounting for a wide range of applications from single rooftop assessments, typically performed by individuals, to large-scale, aggregate-level analyses undertaken by municipal authorities and other large entities. Larger-scale applications typically precede establishment of the optimal level and mix of incentives to stimulate this form of decentralised generation while, at the same time, ensuring the long-term viability of traditional power supply markets.

In the past, the need for specific expertise and the significant costs to develop these simulators have limited their use to advanced economies with well-established electricity markets and a strong research culture. This study finds that the technology landscape has evolved and that solar simulators can now be deployed to maximum benefit anywhere in the world at an affordable cost.

Major cost drivers – 3D rooftop footprint generation and solar irradiation modelling – can now be achieved at significantly lower cost with reasonable accuracy. The quality of satellite imagery required for modelling at this scale can now be produced with a resolution as high as 30 centimetres.

> The typical energy supply challenges cities face range from ageing infrastructure and high consumer prices, mainly in developed cities, to efficiency and reliability issues, typically seen in the cities of developing countries.

In addition, the emergence of cloud computing solutions coupled with advancements in solar irradiation modelling – especially techniques that account for the tilt and shading typical of modern multifaceted roofing architecture – mean that the solar potential of rooftops can now be captured and modelled more accurately. This potential is subsequently provided as an input to complex economic models that examine multiple pathways to sustainable rooftop solar markets in cities.

As encouraging as this is, each individual city faces its own challenges. That is, while modelling techniques may be similar, energy services vary between cities. Thus, simulation of energy services and any subsequent shift in them must be tailored individually to the level of policy and market maturity in each city.

On this issue, the study finds that existing solar simulators, tuned to the business and regulatory setting of developed cities, may not readily be applicable to the developing world without considerable reworking. This is because they do not incorporate the issues faced by cities in these countries, where energy access and affordability are constrained, and where private-sector participation in the energy sector is limited. Furthermore, the regulatory regimes in these settings are often not sophisticated and still skewed towards traditional generators.

The solar PV potential of rooftops in developing cities can now be captured and modelled more accurately using low-cost solar simulators

Accordingly, this study provides a breakdown of potential policy design cases for low-cost solar city simulators. The opportunity for rooftop PV markets in developing countries is highlighted with a detailed explanation of the techniques required to build cost-effective simulators that can be deployed with considerable ease in these settings. Finally, the study highlights the ongoing effort of the International Renewable Energy Agency (IRENA) to use the expertise, data-sharing and hosting capabilities of its Global Atlas for Renewable Energy in demonstrating this technology in selected cities in Uganda and China.

The findings of this work should motivate further dialogue on energy planning in the urban context. More importantly, they make the case for greater use of proven data-driven techniques – such as solar simulators – in creating actionable, pragmatic policy and economic solutions for enhancing energy sustainability in cities in developing countries.

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INTRODUCTION

This report has been prepared to assist cities around the world to take advantage of new developments in solar simulation technology to meet their increasing energy needs. It focuses on aspects of these developments – technology and expertise, mostly pioneered in developed countries – that can be transferred cost-effectively to help alleviate the energy challenges of cities in the developing world.

With this focus, the report explains how city energy planning can benefit from an enhanced understanding of the potential of rooftop solar, appealing both to local municipalities at an aggregate scale and home owners on a small scale. It highlights aspects of the process that can be achieved at a cost significantly lower than previously possible, and presents particular cases where outputs are adapted to the most pressing issues being faced in these settings.

The report opens with an appraisal of the opportunity, shedding light on the common issues faced by cities in most developing countries – growing demand, access, reliability and affordability. It explains the evolving trends in innovation in this space, requiring sound data-driven policies and regulatory regimes to increase access to clean and sustainable energy services in cities in developing countries.

Next, the report explains the findings from an extensive literature review of the methods for developing citywide solar simulators and their application, detailing instances where the results can feed into key processes such as target setting, policy design and market facilitation. It explains key aspects of the modelling process (i.e. three-dimensional [3D] building footprint generation and rooftop solar resource estimation) that were hitherto only achievable at significantly higher cost. It also documents a potential alternative that can enable these tools to be applied at significantly lower cost and adapted to the needs of these cities.

Further, the report provides an extensive overview of these needs, segmenting various cases and establishing four practically applicable scenarios for the use of solar city simulators in developing countries. These include studying the economics of solar photovoltaic (PV) generation and the impacts of rooftop PV electricity production; assessing potential ways to boost access to or improve intermittent supply of electricity; investigating options to reduce consumer prices for electricity through rooftop PV programmes; and finally, assessing the opportunities for end-use sector coupling (e.g. solar heating and cooling, transport).

Finally, the report outlines the International Renewable Energy Agency (IRENA) plan to demonstrate these simulators in two cities, one in China and another in Uganda, capitalising on the technical capabilities of its *Global Atlas for Renewable Energy*. The report provides initial insights into the key functionalities and outputs that can be expected from IRENA's pilot implementation of low-cost simulators. It also features two annexes, one providing a list of examples of solar simulators deployed mostly in cities in developed economies, and a second reviewing the technical process for developing citywide solar irradiation rooftop models.

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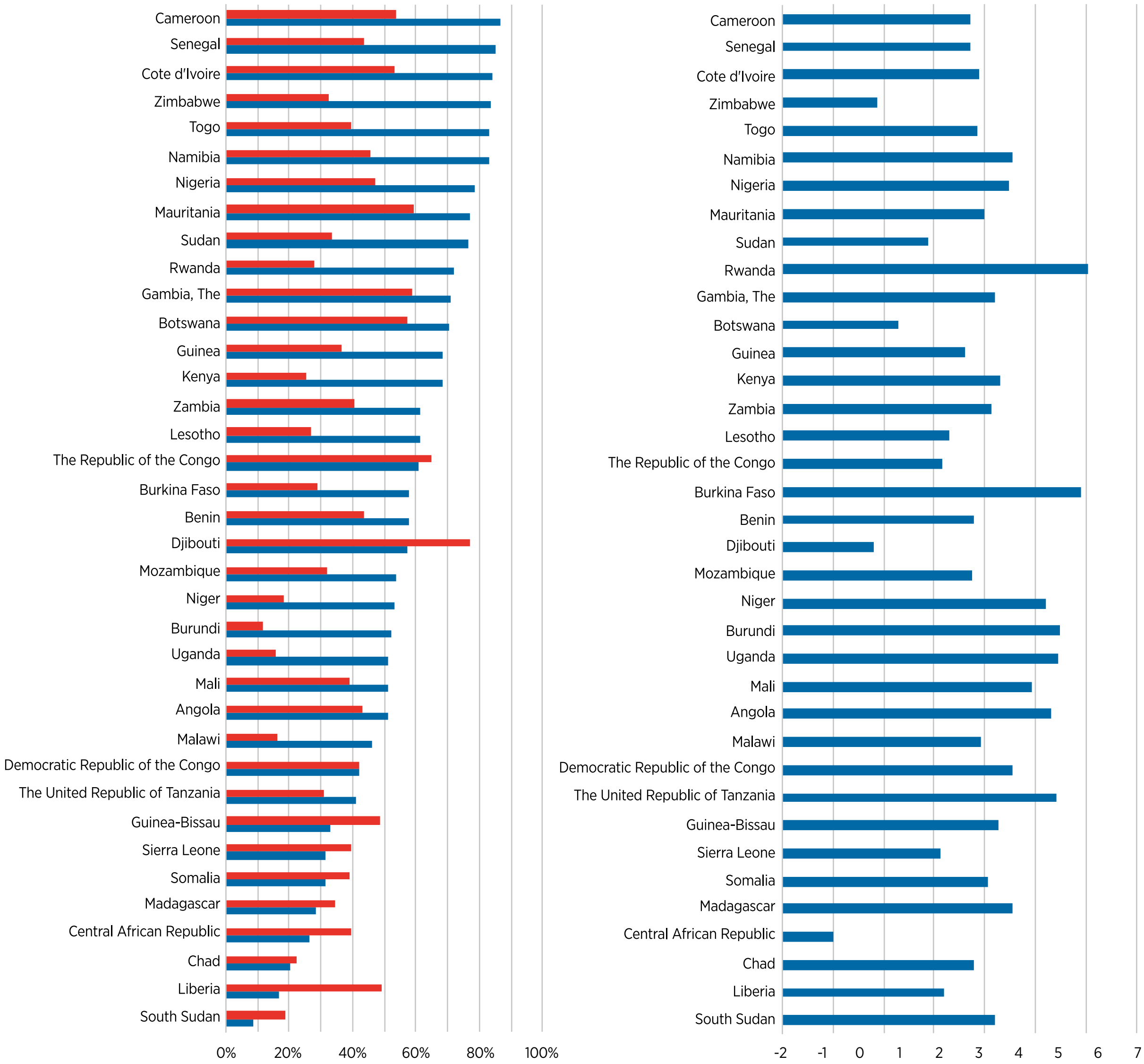
1. URBAN ENERGY CHALLENGES AND THE NEED FOR SOLAR SIMULATORS

Demand growth and access

By 2050 two-thirds of the global population is expected to live in urban areas, with most of the growth occurring in Africa and Asia. The trend is clear in large cities such as Delhi, Dhaka, Jakarta, Rio de Janeiro and Shanghai, where electricity demand grew by factors between 1.5 and 2.0 in the decade 2001 to 2011.(ibid.) This rapid pace of urbanisation is creating a massive surge in demand for energy services and the electricity they require.

Currently, however, more than 130 million people lack access to electricity in urban areas, with 95 million of these living in sub-Saharan Africa (World Bank, 2017). Figure 1, for example, illustrates the situation in a number of countries in the subcontinent as of 2014. As highlighted, while the urban growth rate tops 4% in most of the countries, a significant proportion of residents are still without access to electricity.

Figure 1: Countries in sub-Saharan Africa with below 80% electricity access in urban areas, 2014



Notes: The left-hand chart illustrates electricity access in urban areas as a percentage of the urban population (blue), and the urban population as a percentage of the total population (red). The right-hand chart represents the annual rate of growth of the urban population in percentage terms.
Based on World Bank (2017), World Bank Open Data, https://data.worldbank.org.

Reliability
In countries with greater than average urban electricity access, the reliability of supply is a challenge. For example, although 30% of the population in Africa and 60% in Southeast Asia are reportedly connected to an electricity grid, the service is often infrequent, with disruptions that compel consumers to rely on back-up generators at a high cost (ESMAP, 2017).

These disruptions result in a loss of productive capacity for business and they negatively impact the standard of living of residents. In 2016, for example, the loss of value to business due to electrical outages in sub-Saharan Africa was quoted at 8%. In the Middle East and North Africa these losses reached 5.9%, and 3% in East Asia and the Pacific. By comparison, they are less than 1% in the European Union (World Bank, 2017).

Potential solutions
With the rapidly falling price of rooftop PV systems and smart system design, this option is becoming attractive and reliable, offering competitive economics compared to the extension of grids (IRENA, 2017). Rooftop PV installations can bring value to residential and commercial buildings by supplying electricity during grid outages, as well as increasing the resilience of the electricity system (NREL, 2014). In India, for example, Sundaray et al. (2014) highlight the value of rooftop PV in compensating for the regular power outages experienced in most Indian cities due to load shedding.

This shedding and consequent loss of productivity also are mentioned as the main drivers for assessing the potential of rooftop PV in other developing-country cities: see, for example, Adeleke and Smit (2016) for South Africa; Khan (2016) for Pakistan; and Luqman et al. (2015) for Lahore. In this context, simulators capture the potential for decentralised rooftop installations. This makes them essential to modelling solar-based business and policy solutions.

1.1. Solar simulators for cities in developing countries

The energy services landscape is evolving rapidly. With the falling cost of PV systems and wide-ranging innovation – net-metering, microgrids and electric mobility on the engineering front, and the evolution of business and financing models and payment systems – there is no a better time for cities to incorporate rooftop PV solutions into their supply mix. Municipal planners in these cities, however, need to develop sound data-driven policies and regulatory regimes to incentivise this process. More pertinently, these policies need to reflect the economic realities of these cities, particularly in developing countries where – as indicated earlier – the issue is a dire need.

Developing this enabling framework for the most part can be quite complex and expensive, depending on the approach taken. It typically starts with a citywide assessment of the rooftop solar potential, where the total available rooftop surface of the entire city is established and then delimited to determine the share of the surface that is suitable for installing solar PV. Castellanos, Sunte and Kammen (2017) distinguish three categories of methods to do this:

- Sampling methodology: A calculation is made of the total available roof surface, based on a detailed analysis over a sample area that is generalised to the entire city.
- Multivariate sampling methodology: The rooftop area per capita is calculated using population density correlated with the types of building and the available area. This is then multiplied by the total city population.
- Complete census methodology: The entire rooftop area is computed by producing either statistical datasets that contain building information (i.e. proportions of commercial, residential and industrial buildings) or by carrying out an analysis by way of a geographic information system (GIS) with 3D models of the city.

Rooftop PV supplies residential and commercial power during grid outages and increases the resilience of the whole electricity system

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The results obtained, using any of these methods, ultimately feed into studies that assess suitable policy options to improve the supply, efficiency and sustainability of energy in these cities. In principle, this outcome is achievable through desktop research and anecdotal experience from other cities.

It is also achievable through initial demonstrations on a sample of buildings. For example, Ethekwini – a small municipality in the city of Durban, South Africa – installed solar PV systems on five of its municipal buildings in 2017 to learn about the daily and yearly generation profiles obtainable from these systems. One of the main objectives of this pilot was to create enough local experience of PV systems to develop policies that would guide their deployment across the entire municipality.

The anecdotal approach to policy analysis and design is obviously susceptible to potential flaws, as knowledge gaps can result from limited understanding of all potential outcomes of deployment, with a fuller understanding obtainable only through multiple simulations. Pilot implementation, conversely, can be costly. Pilots require time and do not necessarily guarantee representative results. This is where solar simulators that apply complete census methods play a key role, as they provide the capacity to pre-emptively analyse several outcomes prior to roll-out.

Solar simulators employ cutting-edge technology that combines know-how in remote sensing, high-performance data processing, 3D building footprint generation and solar irradiation modelling. They are by far the most accurate methodology, can be deployed to study entire cities, and can be applied to support target setting, policy design and market facilitation.

They can also be tuned to provide a variety of outputs, including estimates of the installable capacity and generation potential of each rooftop, directly relevant to individual homeowners and property investors, but also very useful for city planning when output is aggregated. Examples of solar simulators include Google's Project Sunroof[1] and MIT's Mapdwell.[2]

Annex 1 provides a non-exhaustive list of places that have employed interactive rooftop solar simulators. As a result they have enabling frameworks with sound policies to lessen the risks associated with investing in rooftop PV. Most of these platforms have been made public and interactive to reach the targeted audience. They form the knowledge base from which to exploit solar energy (Kanters, Wall and Kjellsson, 2014).

The listed cities are, however, exclusively in developed countries with a strong research culture and funding base, where key ingredients of a simulator, such as 3D city plans based on expensive airborne light detection and ranging (LiDAR) measurements, already exist. For the most part, these simulators are also used in other areas of analysis, including estate and infrastructure development.

Therefore, bringing the value of this technology to cities in developing countries would require significant adaptation, both in the technical methodologies – to save cost – and in the development of business cases that adequately reflect these cities' characteristics. The subsequent parts of this report review in detail the current methods deployed in developing existing solar simulators. The limitations of these methods are highlighted, with an emphasis on the need for their adaptation to solve problems in developing-country cities. It provides insight into a revised cost-competitive approach that can be deployed with considerable ease in such places.

The work also provides a general breakdown of potential cases for the use of simulators, with a solution-focused approach to urban energy planning. It highlights important international influencers, such as the New Urban Agenda adopted by the United Nations General Assembly in resolution 71/256 of 23 December 2016, which could support the push for their deployment across several cities and communities in the developing world.

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1. See *www.google.com/get/sunroof#p=0* for more information.
2. See *www.mapdwell.com/en/solar* for more information.

2. SOLAR CITY SIMULATORS: APPLICATIONS AND ALTERNATIVE METHODS

Kanters, Wall and Kjellsson (2014) have compared the outputs and impacts of 19 solar simulators in 8 countries. Half of the cadastres in their review were designed to illustrate the level of incoming solar irradiation on rooftops, while the other half simulate the PV output (technical potential). In terms of impact, the city of Basel in Switzerland was cited as an example where the deployment of a solar city simulator encouraged citizens to renovate their roofs so that solar PV systems could be installed on 500 of them.

Nevertheless, the level of complexity of solar simulators varies significantly, from simple static maps describing the potential suitability of a rooftop PV system (e.g. from high to low), to tools that pre-calculate technical potential under fixed assumptions (e.g. production, investment, net present value), to fully interactive technical and financial simulators. IRENA's literature review supports the classification of solar cadastres by complexity level, as proposed by Kanters, Wall and Kjellsson (2014):

- Basic: Indicates irradiation levels and their categorisation (e.g. high, medium, low irradiation values).

- Medium: Indicates irradiation levels, solar system outputs, categorisation of suitable area for solar production and system effect.

- Advanced: Indicates irradiation levels, system (PV, thermal) output, categorisation of suitable area for solar production, system effect, monthly output, financial considerations, information about installers and data regarding solar energy.

The new generation of advanced online solar simulators can provide analytical support in three major opportunity areas:

- Opportunity 1: target setting: high-level data to provide a broad analysis of solar PV rooftop potential.

- Opportunity 2: policy design: detailed information required to deliver an effective and efficient business case to achieve objectives.

- Opportunity 3: market growth: support to citizens, financers and installers in order to lower investment barriers and risks of investing, as well as increase the volume of installations.

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Opportunity 1: Target setting

Setting renewable energy targets is a policy-driven process that uses evaluations of the renewable energy potential as a knowledge base. Solar simulators can support this by providing an evidence- and data-based analysis of solar PV rooftop potential. The analysis establishes the suitability of rooftop areas, corresponding installable capacity, production potential, and levelised cost of electricity (LCOE), particularly for public buildings (AfDB, 2017).

At this level the prevailing preference is for high-level approaches, whereby an initial assessment is made through sampling and extrapolation (Amado and Poggi, 2014a; Gagnon et al., 2016; Sundaray et al., 2014; Wiginton, Nguyen and Pearce, 2010). With more time and effort, solar simulators that are developed using census methodologies result in more accurate analysis. At such an early stage (target setting), however, the use of this approach should be limited, in the event the municipality does not proceed with solar PV as an option for the city's energy supply.

Opportunity 2: Policy design

Post target setting, once the municipal authorities are convinced of the solar potential for their city as derived either from simplified estimates or advanced solar simulators, the need for an appropriate policy framework arises. This brings more complexity with regard to the granularity of data and required modelling, and is the environment in which solar simulators are most valuable, since they provide a precise vision of the solar rooftop potential.

Solar simulators are used in the design of these policy frameworks, which may include investment incentives, attractive business models (Sundaray et al., 2014) and various tariff scenarios (Martin and Rice, 2018), often in combination. A simulation of the distribution grids with a large share of rooftop solar PV may also be made available.

The target audience for solar simulators as applied to policy design are those cities that are sufficiently ambitious to pursue renewable energy alternatives, and which are in the process of developing relevant regulations. These cities may be participants in or members of the Sustainable Cities Integrated Approach Pilot programme (supported by the Global Environment Facility [GEF, 2017]); the World Bank's Global Platform for Sustainable Cities; the International Council for Local Environmental Initiatives (ICLEI) (1 500 members); or the Covenant of Mayors (7 700 signatories). The main outcomes of policy design are evidence-based recommendations and the enhanced capacity of local policy makers in urban energy planning, together with the solar simulator (cadastre) as a knowledge base.

Opportunity 3: Market facilitation

During implementation of local policy, advanced solar simulators (as presented previously) that are publicly available (web-based) can help identify projects that are potentially profitable, while taking into account the local enabling environment. These online platforms are currently of commercial value and are managed by start-up companies. They operate in countries where the policy framework has reached maturity and the rooftop PV market is sufficiently large to allow these start-ups to sell solar simulators or analysis as a service to municipalities, and/or to use them to connect consumers and installers. At this stage, the most comprehensive online solar simulators are essentially business-to-business and business-to-consumer multi-dimensional platforms that compare electricity demand with supply for each building in the city, and highlight the need for and prospective gains from rooftop installation.

2.1. Developing solar simulators based on a complete census approach

The creation of a solar simulator can be summarised by a four-step workflow, adapted from Lukač et al. (2013) and Gagnon et al. (2016), as follows:

- creation of detailed 3D building footprint and digital elevation model (DEM)
- simulation of solar rooftop resource
- identification of suitable roof areas
- simulation of rooftop systems.

These steps provide a geospatial dataset relating to city rooftops. Each polygon (building rooftop) includes information on the height, azimuth, tilt and suitable area(s) of the rooftop, installable capacity and generation potential.

The creation of the 3D building footprint and DEM represent the major cost drivers in the process, which could significantly hinder their deployment in low-income countries. Existing techniques create these by using LiDAR measurement campaigns, which are highly detailed and extremely expensive. The spatial resolution of these input datasets (in centimetres [cm]), reflecting the close accuracy of this method, represents the city while capturing detailed features such as sharp elevation changes in complex rooftop structures.

Using attributes of the 3D building rooftop structures, an estimate of the solar irradiation captured on the surface of each rooftop – and, consequently, the generation potential – can be computed. These pro-forma solar resource generation estimates rely on methods developed to calculate the irradiation on tilted surfaces, which effectively transpose the direct normal (DNI), the diffuse horizontal (DHI) and the ground-reflected irradiation components (see detailed model review in Annex 2). Critical factors, such as shading, are accounted for and used to limit the rooftops to suitable portions upon which PV cells should be installed. This area then forms the basis of rooftop system simulations to estimate generation capacity (Annex 2).

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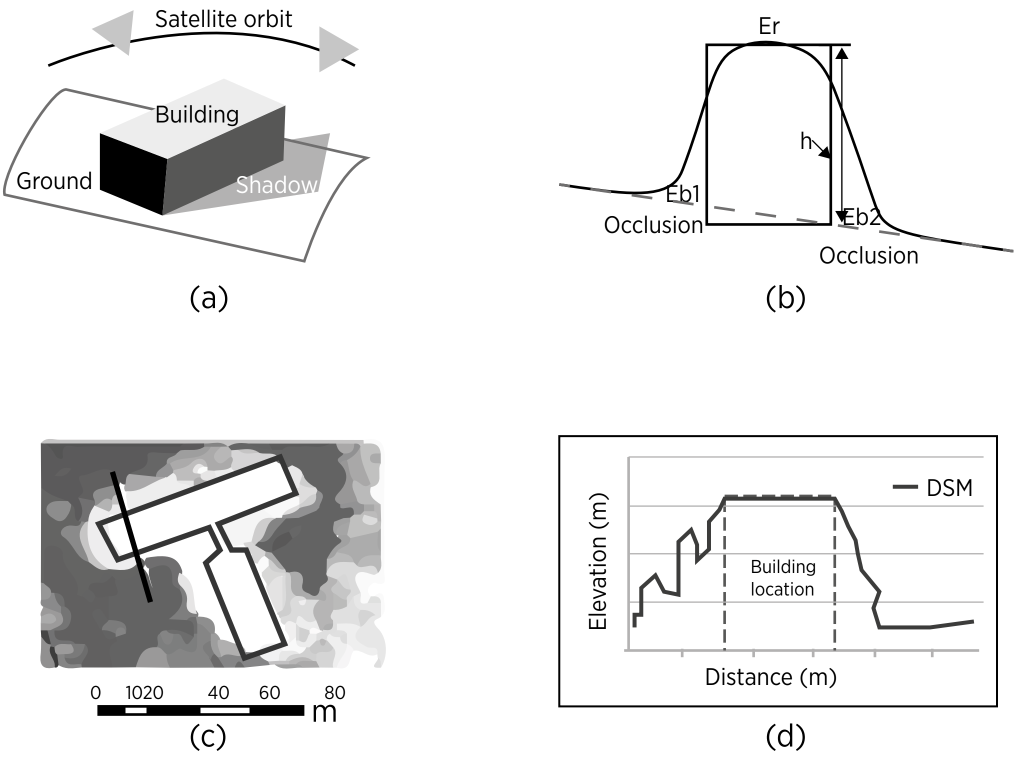
2.2. Emerging alternative to expensive 3D building footprint and DEM generation

An alternative approach to LiDAR measurement campaigns in the generation of the 3D building footprints and DEMs, which is deemed to be less expensive, relies on stereoscopy (photogrammetric techniques) that use high-resolution satellite imagery (up to 30 cm spatial resolution) as input.

For illustrative purposes, IRENA conducted an in-house exercise to develop a DEM from a pair of stereoscopic images at 50 cm resolution, representing two perspectives of the same scene (buildings in a city). The height (elevation) of each building was estimated by processing an ortho-rectified pair of images and combining them to observe the parallax between the exact features in the same position. The DEM from this could then be segmented and further processed to create representations of each rooftop's structure and, eventually, the 3D building rooftop model of the city.

Although the DEM from this exercise identifies the rooftop locations (Figure 2), the results require additional refinement to be practically applicable. Specifically, manual edits are necessary at the edges of complex roof types to correct classification errors due to shade or other image noise phenomena, and also to account for obstructions such as trees, water tanks or mounted structures on rooftops (Figure 3).

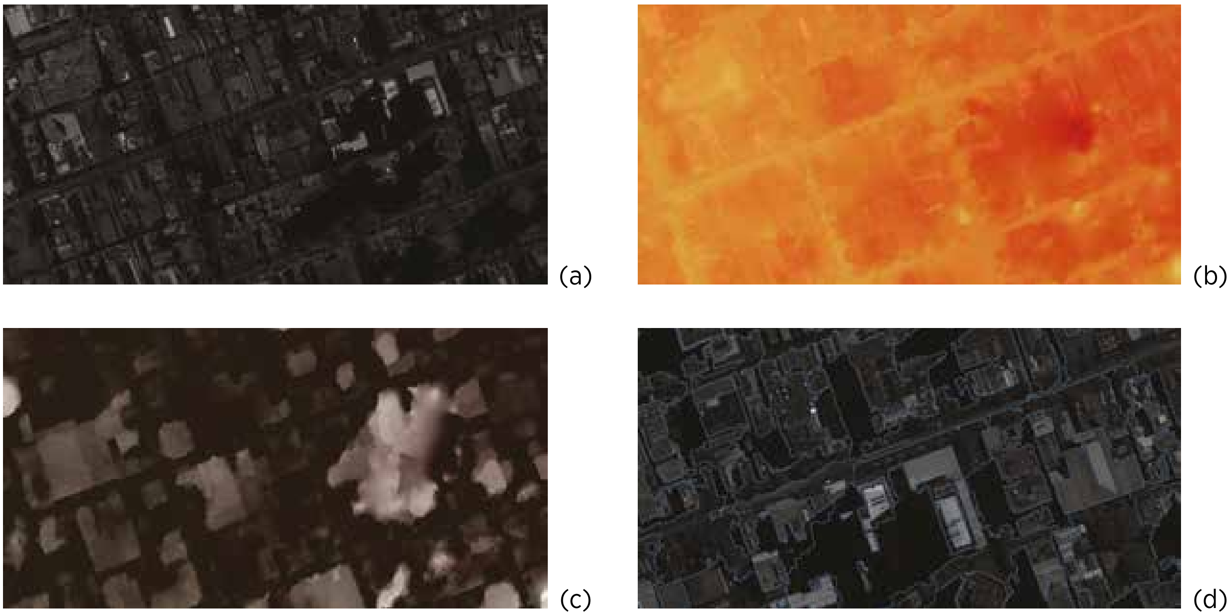
Figure 2: Approach and uncertainties of DEM generation from stereo imaging



(a) (b) (c) (d)

Notes: A building is imaged twice (a), with a difference in parallax; the curve in (b) represents the colour gradient for a cross-section of the building (the rooftop edge is not sharply identified, and the actual elevation differs from the calculated height); (c) the grey-coded elevation and the actual building edges are overlaid in black lines; and the elevation profile across the line is observed in (d); artefacts next to the building location may confuse automated recognition software.
Source: Zeng, Chuiqing (2014), "Automated building information extraction and evaluation from high-resolution remotely sensed data", *https://ir.lib.uwo.ca/etd/2076*.

Figure 3: Reconstruction of city DEM from stereo imaging



Notes: Internal simulation using sample satellite images over Melbourne for testing purposes: (a) mosaicked Tri-stero panchromatic image bundle shows; (b) the digital terrain model created from ortho-rectified stereoscopic images with resolution at 50 cm; in areas with strong elevation gradients, shading is the cause of difficulties in extracting the elevation ; (c) initial outlines of rooftops are extracted from one of the ortho-images; (d) both inputs are combined to assign an elevation and to delineate the sections of each rooftop. The artefacts on some of the buildings are not properly captured in the digital elevation and terrain model which result in notable omissions in the rooftop segmentation in this image. To correct this, manual edits are required.

Source: Internal simulation produced by IRENA using Airbus (2012), Sample Imagery: Pleiades Tri-stereo panchromatic bundle for Melbourne Australia, *www.intelligence-airbusds.com/en/8262-sample-imagery*.

Although commercial software programs, such as PCI Geomatica used in IRENA's previously mentioned exercise, allow the processing of stereo images, the generation of a high-resolution DEM for an entire city requires significant computational capabilities and skills. The study found these to be obtainable with varying levels of accuracy from a number of private companies, for a fee, for any location in the world due to the availability of high-resolution satellite imagery. The quality of the output, however, may vary depending on the resolution of data input.

Notably, LiDAR and stereoscopy alike produce clouds of elevation points, with the former being better due to the ultra-high resolution, possibly less than 10 cm. The cost of LiDAR campaigns, however, can run into the millions of US dollars for cities 20–30 square kilometres in size – hence the reason 3D building footprint data and high-resolution DEMs are not readily available in developing countries.

Although LiDAR campaigns (sometimes coupled with aerial imagery) remain the ideal option, satellite imagery based stereoscopic modelling – achievable for under USD 50 000 for a similar area – provides an inexpensive and fairly accurate option that can be deployed rapidly in developing countries to build the essential data input for the solar resource modelling process. The required overlapping satellite images are, in general, available at 50 cm resolution globally[3] and, in some instances, at 30 cm resolution from DigitalGlobe's WorldView-3 and Worldview-4 satellites. The availability of such images taken in conditions that allow for stereoscopic pairing depends on the latitude of the city, with frequencies improving at higher latitudes.

Agugiaro et al. (2012) compare the performance of 50 cm resolution images with those of 25 cm and conclude that the former would be sufficient to extract the rooftop surfaces and required attributes (tilt and azimuth) for rooftop PV simulation. At that scale, the detailed structure of the roof (e.g. presence of chimneys and other artefacts) would remain unknown.

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[3] The satellite coverage can be tested online. See DigitalGlobe at https://discover.digitalglobe.com and LandInfo Worldwide Mapping LLC at http://search.landinfo.com/. For some campaigns, images can be downloaded from US Geological Survey archives at https://earthexplorer.usgs.gov (accessed March 2018).

3. LOW-COST SIMULATORS FOR SOLAR POLICY DESIGN

Having established in earlier chapters the technical feasibility of developing and running solar simulators, the next question is how these simulators can practically make a difference for cities in the developing world. In other words, what impact can solar simulators have on improving the accessibility, affordability and reliability of electricity supplies?

Building the use-case scenario requires a preliminary assessment of each city's strategy, with the aim of reaching solutions that are tailored to local needs (design thinking). The sections that follow discuss some of the issues that developing-country cities may face, based on the body of literature reviewed:

- Case 1 provides a baseline scenario: the interest in growing rooftop PV is driven by the economics of the technology and the opportunity to reduce the carbon dioxide impacts of electricity production.

- Case 2 presents constrained access based on supply: the main issue is the lack of access to or intermittent supply of electricity, rather than that of pricing.

- Case 3 presents constrained access based on prices: the prospective cost of grid extension, especially to remote communities, results in electricity prices that hamper economic and social development.

- Case 4 offers a sustainable city scenario: the municipality investigates the opportunities for modern energy services and sector coupling (e.g. coupling solar with heating and cooling or with transport).

Building the use-case scenario for solar simulators requires a preliminary assessment of each city's energy strategy

Case 1. Accessible, affordable and reliable electricity supply

This is the current environment in which solar simulators have been produced so far (see list in Annex 2). In this case, specific attention is paid to taking advantage of falling PV production costs where grid parity has been reached or surpassed. Simulations are based on the expectation that the electricity produced would satisfy household demand either partially or completely. The existing simulators that address this case have options to assume gross or net metering, allowing the economics of a PV system to be assessed in an interactive fashion based on available financial incentives. The decision of a building owner to invest in a PV system is assumed to be one based on a comparison of the system's LCOE against the electricity retail price, accounting for possible local tax exemptions, premiums or tariffs.

Case 2. Unreliable electricity supply

In this case, solar PV adds value by bridging the gap created by electricity demand that is unsatisfied. When backup power capacity is used, the economics of the PV system is compared to the LCOE of alternatives (e.g. diesel generator, kerosene). In such case, the solar PV system improves access by lowering the kilowatt hour price. When there is no alternative, however, the PV system may improve access by increasing power reliability and daily energy availability.

A major variance in this scenario would be the addition of storage for a single household, or for mini-grids at the district level. This level of simulation requires a more complex supply and demand analysis, as well as a review of load profiles. IRENA's online Project Navigator offers a residential solar PV evaluation model that includes storage criteria (IRENA, 2018).

Case 3. High electricity prices due to excessive grid extension costs

In this case, rooftop PV is investigated as an alternative to extending the electricity grid to remote communities or creating standalone electricity grids – which could give rise to electricity prices that are exorbitant, that constrain demand for the service, and consequently result in adverse impacts on the local economy. The main dimensioning parameters include the load and production profiles, investment costs, and capital and maintenance costs (e.g. inverter).

Case 4. End-use sector coupling

Accelerated urbanisation rates translate into an urgent demand for improved infrastructure, services and institutions. The complexity of urban infrastructure requires collaboration at the highest levels to address multiple-sector coupling, referred to as the Urban Nexus in GIZ and ICLEI (2014). Urban issues are complex and require solar simulators to provide the necessary baseline information to conduct an analysis of energy policy. A prime example for reference is electric mobility (e-mobility).

The global market for electric vehicles is growing at a rapid pace, having exceeded 2 million units in 2016 (IEA, 2017). Electric cars outnumber public charging stations at a 6:1 ratio, and most drivers rely on private charging stations to power their vehicles.

According to the International Energy Agency (IEA, 2017) and Bauer et al. (2017), the e-mobility sector is expected to create important sector coupling opportunities and could change demand profiles. One option to mitigate the impacts of electric vehicle charging is to incentivise self-consumption through solar systems (IEA, 2017). This is a case of sector coupling that is examined by Byrd et al. (2013). A high-resolution solar simulator is used to simulate daily net-metering patterns and assess the energy absorption of electric vehicles through self-consumption.

> One option to mitigate the effect of electric vehicle charging on the electricity system in cities in the future will be to encourage self consumption through solar PV.

4. AN IRENA SOLAR CITY SIMULATOR: DEMONSTRATION IN UGANDA AND CHINA

The Global Atlas for Renewable Energy is IRENA's platform to promote best practices in renewable energy resource assessment globally. It comprises a web-based geographic information platform, coupled with offline zoning and site assessment services aimed at facilitating the development of renewable energy markets worldwide. The web platform provides access to more than 2 000 renewable energy maps covering solar, wind, geothermal, biomass and tidal energy, and has played host to more than 200 000 online professionals since 2013.

Drawing on the technical expertise, datasets and network built around the platform over the years, IRENA is in the process of demonstrating a pilot solar city simulator – the SolarCityEngine – in the cities of Kasese in Uganda and Zhangjiakou in China. While the demonstration in Zhangjiakou is yet to start, that in Kasese has progressed significantly. In Kasese, a settlement with a population of slightly more than a 100 000 people, Case 1 and Case 2 will be tested.

The solar simulator for Kasese – now quite advanced in design – addresses purchase and lease financing options for rooftop solar PV installations in the city, with three business cases:

- That of an individual home owner seeking to compare rooftop PV to alternatives.
- An estate promoter investigating the prospects of a small community (group of buildings) being equipped with rooftop solar.
- A simplified case of a municipality investigating the cost of different policy options on a broad scale, across the entire city.

For individual homes and small communities, this simulator allows for the dynamic optimisation of PV systems on rooftops in the city and generates several key decision factors, such as total available surface area, installable capacity, generation potential, total investment cost, LCOE, net present value and savings, among others. The same tool also helps to investigate the long-term benefits of rooftop PV installations in load-shedding situations compared to alternatives (e.g. small gasoline generator sets).

For municipal authorities, the system optimises installations for the entire city, assuming the best areas are equipped to meet target capacity. It allows for highly simplified simulations of the impact of a limited list of policy options – on the viability and affordability of rooftop systems in the community. One example addressed in this tool is the effect of import tax reductions on the tariff (under a lease model) for a target installed capacity across the city. The outputs may include the total volume of investment created, the value per unit of government spending, and indices to estimate affordability, i.e. the per kilowatt-hour PV electricity price as a percentage of daily household income, and the quantity of electricity that can be purchased at this price with 10% of daily household income.

This demonstration is intended to highlight the opportunities for growth in rooftop installations in Kasese. In addition, and as a consequence, it should stimulate the appetite of municipal authorities in other cities in developing countries to take full advantage of the benefits of low-cost solar simulators.

A simulator for Kasese, Uganda, offers financing options for solar PV installation

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5. CONCLUSION

This report was prepared in the context of ongoing activity by IRENA to demonstrate the impact of deploying low-cost rooftop solar PV simulators, primarily to support the energy transition in cities of developing countries. The report is a product of a detailed review of literature to understand the processes behind solar rooftop PV simulator tools and their effectiveness at providing accurate information on solar potential at a resolution high enough to assess rooftop spaces in cities.

The report concludes that solar PV simulators that embrace cutting-edge technology – combining know-how in remote sensing, high-performance data processing, 3D building footprint generation and solar irradiation modelling – can be deployed cost-effectively in cities in developing countries for a wide range of applications.

Primarily, at the individual level, they can be used to study the economics of a rooftop solar PV installation. For municipalities, they can be used to: assess ways to boost access to electricity or improve intermittent electricity supply; investigate options to reduce consumer prices for electricity through rooftop PV programmes; or to assess the opportunities for end-use sector coupling (e.g. coupling solar heating and cooling with transport).

The report also concludes that these tools – currently only available to cities in developed countries (see Annex 1) – can now be built cost-effectively and deployed in cities in developing countries to provide input to the process of urban planning and, specifically, that of developing solar PV rooftop programmes in these settings.

The findings of this work are intended to motivate further dialogue on energy planning in the urban context. Most importantly, they are meant to spur the increased use of proven data-driven techniques – such as solar simulators – to create actionable and pragmatic policy and economic solutions. Better-informed solutions, in turn, should enhance energy sustainability in the cities of developing countries.

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ANNEX 1. INTERACTIVE SOLAR ROOFTOP SIMULATORS AND CADASTRES: A NON-EXHAUSTIVE LIST

Aachen (Germany)	Geoportal Aachen: https://geoportal.aachen.de/extern/?lang=de&basemap=luftbild2016&blop=1&x=294405.36611213&y=5628845.6132009&zl=15&hl=0&layers=solaranalyse57e2770b86066&theme=3
Amersfoort (the Netherlands)	Amersfoort rooftop solar PV installation and generation potential simulator: http://amersfoort.burokarto.nl
Annecy, Bordeaux, Lyon, Nantes, Paris (France)	Solar cadastres for: Annecy, Bordeaux, Lyon: www.cythelia.fr/energies-renouvelables/expertise/cadastre-solaire/ Nantes https://nantes-metropole.insunwetrust.solar/simulateur Paris: http://capgeo.sig.paris.fr/Apps/CadastreSolaire/
Berlin (Germany)	Berlin Solar Atlas (by business location centre) www.businesslocationcenter.de/wab/maps/solaratlas/?startingmap=ol3&legendposition=left&layerToActivate=solarpotential_gebaeude_2013&groundPosition=13.39848,52.51573&distance=3217.64&headerTitle=Solaratlas+Berlin&lang=de&WAB-REDIRECT=1
Calgary (Canada)	Calgary Solar Potential Map: https://maps.calgary.ca/SolarPotential/
Dusseldorf (Germany)	Rooftop Solar Suitability Indicator for Dusseldorf: http://details.solare-stadt.de/duesseldorf
Geneva (Switzerland)	Solar Cadastre of the Territory of Geneva: www.etat.ge.ch/geoportail/pro/?mapresources=GEOTHERMIE%2CENERGIE_SOLAIRE%2CENERGIE&hidden=GEOTHERMIE%2CENERGIE_SOLAIRE
Graz (Austria)	Geodata Portal of Graz: https://geodaten.graz.at/WebOffice/synserver?project=solar_pv&client=core
Lisbon (Portugal)	Rooftop Solar Potential Platform of Lisbon by Lisboa e.Nova: http://80.251.174.200/lisboae-nova/potencialsolar/
Marburg (Germany)	Solar Cadastre of Marburg: www.gpm-webgis-10.de/geoapp/solarkataster/marburg/
Solingen (Germany)	Rooftop Solar Potential Platform for Solingen: https://stadtplan.solingen.de/buergerservice1/ol3/sg_layout.html?gui=solar&scale=4&x=2576000&y=5671201&wmslayer=1,0
The Netherlands	Zone Atlas of the Netherlands: www.zonatlas.nl/home/
United States	Mapdwell: www.mapdwell.com/en/solar Google sunroof: www.google.com/get/sunroof#p=0
Tyrol (Austria)	SOLAR-TIROL Solar Potential Database: http://webgis.eurac.edu/solartirol/
Vienna (Austria)	Vienna Solar Potential Cadastre: www.wien.gv.at/umweltgut/public/grafik.aspx?ThemePage=9

ANNEX 2. THE SOLAR RESOURCE MODELLING PROCESS

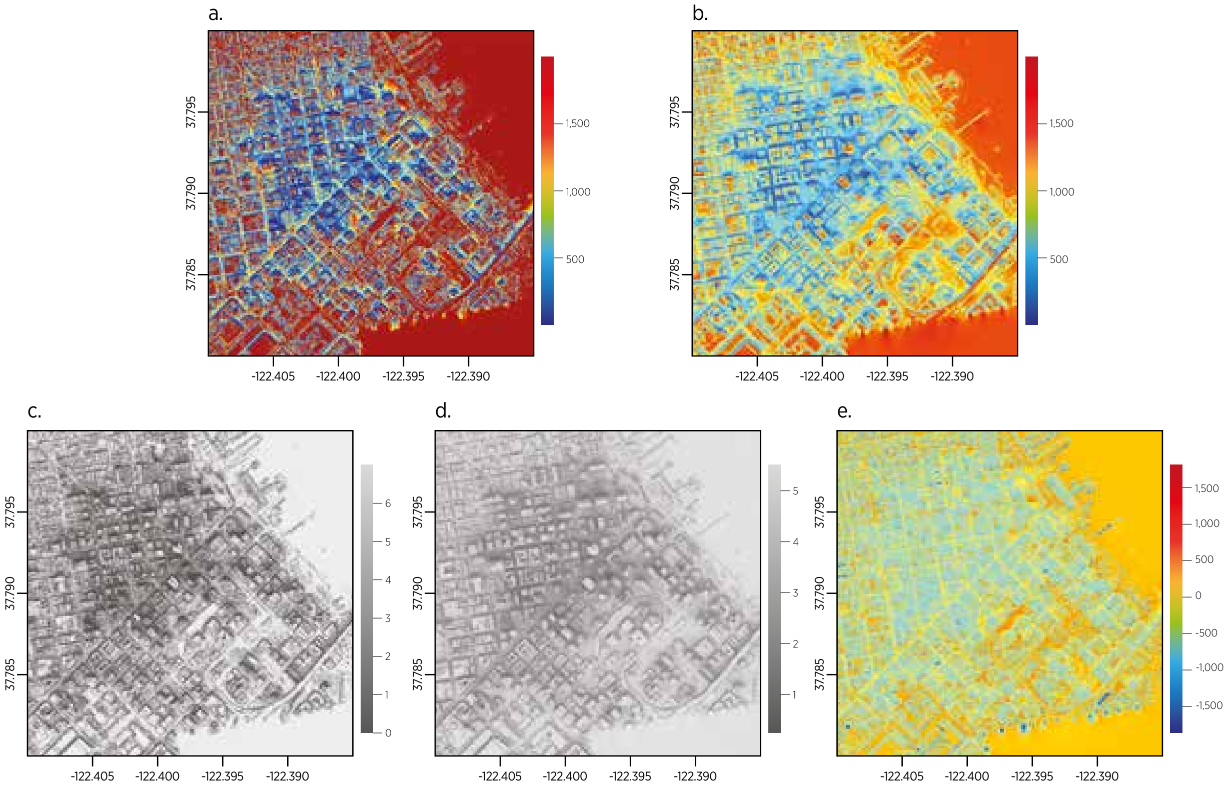
An estimate of solar irradiation on the tilted surfaces of various orientations is essential to simulate the production of PV arrays. For this, transposition models that estimate the solar irradiance incident on tilted PV panels are used. The global horizontal irradiance (GHI) consists of three components: the direct normal, the diffuse and a third component due to reflectance from earth surfaces.

Transposing the direct component is fairly straightforward, using commonly agreed trigonometric transformations that take into account the sun's azimuth and the tilt angle of the location. Where opinions differ is in the handling of the diffuse component. Mubarak et al. (2017) compared five models built for this purpose (i.e. the models of Liu and Jordan, Klucher, Hay and Davies, Reidl and Perez). In their review, anisotropic models offer a finer description of the diffuse component, presenting a higher performance compared to isotropic models, which assume that all directions contribute equally to the diffuse irradiance component (Bourges, 1986).

The influence of isotropy on solar rooftop resource estimation has been calculated by Clean Power Research, comparing the results from current isotropic methods (Figure A2.1(a) and Figure A2.1(c)) to the results obtained with anisotropic methods (Figure A2.1(b) and Figure A2.1(d)). Isotropic methods tend to underestimate the predicted hours of sunlight and irradiation (Figure A2.1(e)).

Beyond isotropy, other elements explain the differences between the two approaches. The isotropic method used in this example was used to evaluate the rooftop potential for the United States. Reflecting the magnitude of this work, attempts were made to optimise the calculation time by binning tilt and azimuth data into 15-degree sectors, discarding north-oriented surfaces and discarding heavily tilted surfaces (above 60 degrees in tilt).

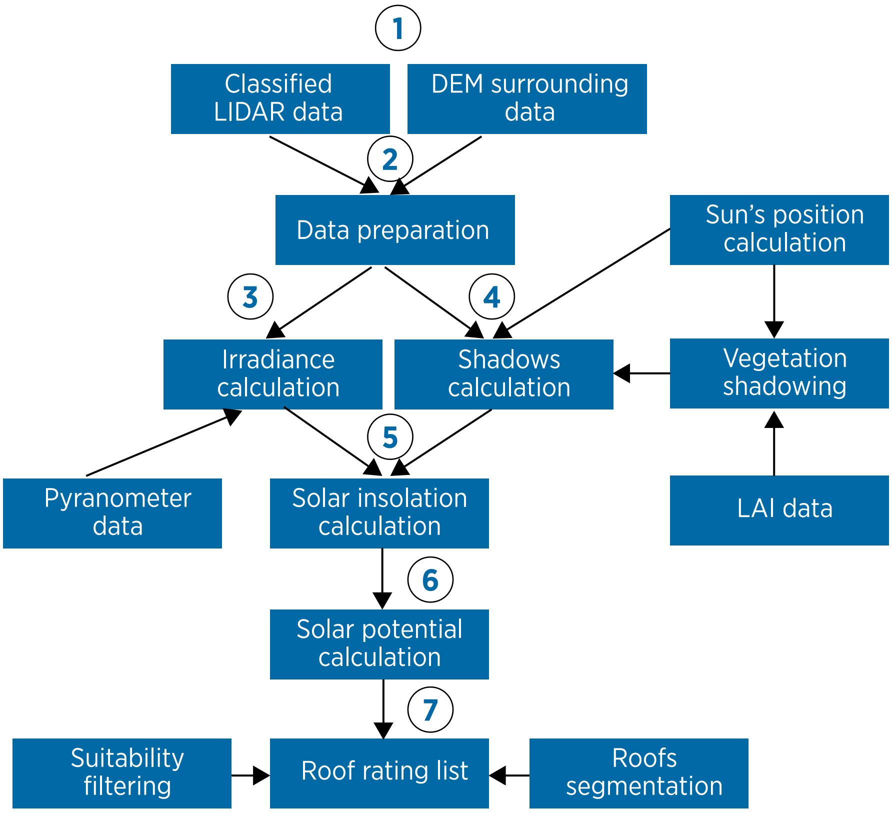
Figure A2.1: Illustration of the influence of anisotropy on solar rooftop resource estimation



Notes: Estimates of annual radiation in kilowatt hour/square metre/year from (a) isotropic method and (b) anisotropic method; predicted number of hours of sunlight with (c) isotropic method and (d) anisotropic method; the error map (isotropic–anisotropic) in kilowatt hour/square metre/year is presented in (e).
Source: Clean Power Research.

Once calculated on a tilted plane, the irradiance values should be corrected for shadowing effects from neighbouring buildings and vegetation. Lukač et al. (2013) detailed a methodology using an isotropic transposition model. While the irradiance calculation differs, their approach to shadowing calculations is similar to the open-source software r.sun[4] and the ArcGIS solar analyst (Wolfs, 2017).

Figure A2.2: Solar cadastre generation workflow



Notes: Irradiance, shadows and vegetation shadowing are considered separately, and combined to calculate the solar insolation at any given point of the rooftop area; LAI = leaf area index.
Source: Lukač, N. et al. (2013), "Rating of roofs' surfaces regarding their solar potential and suitability for PV systems, based on LiDAR data", Applied Energy, Vol. 102, pp. 803–12.

As explained in Lukač et al. (2013) (Figure A2.2), the irradiance at any point is calculated in a time-dependent manner (e.g. hourly, although r.sun indicates a 30-minute timestamp) by weighting the direct irradiation component on the tilted surface with a shading coefficient. The shadowing is assumed to affect only the direct tilted irradiation (DTI) component. The diffuse horizontal irradiation (DHI) component remaining unaffected.

These assumptions lead to a simplified instantaneous global tilted irradiance (GTI) on a tilted surface that becomes, at any moment t:

$GTI\ (t) = DTI\ (t)\ (1 - S) + DHI\ (t)$, where:

- S is the shadowing effect, which is discussed below.
- DTI and DHI have previously been transposed from their horizontal components to the tilted surface (i.e. the rooftop surface or PV panel surface) using a transposition model. The model discussed here includes the direct and diffuse irradiance components and does not include the reflected component due to the albedo of the ground surface, which is assumed to be negligible.

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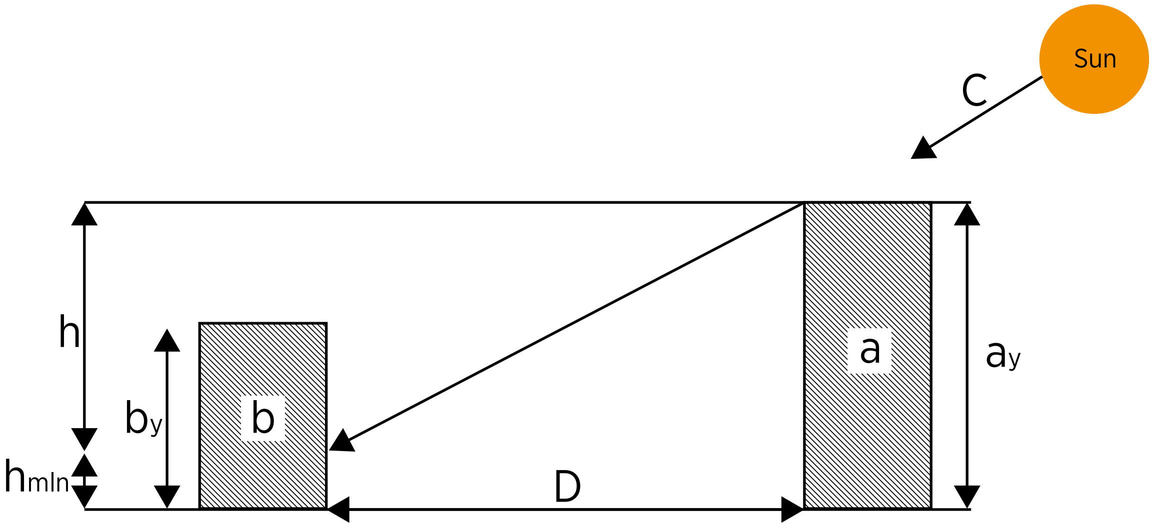
4. See https://grass.osgeo.org/grass74/manuals/r.sun.html (accessed April 2018).
5. See PV Performance Modeling Collaborative at *https://pvpmc.sandia.gov/modeling-steps/1-weather-design-inputs/plane-of-array-poa-irradiance/calculating-poa-irradiance/poa-sky-diffuse/* (accessed on March 2018).

The GTI is calculated for each unit of time and, therefore, the daily irradiation value is the integral of the values between sunrise and sunset. The annual potential is the average daily insolation throughout the year.

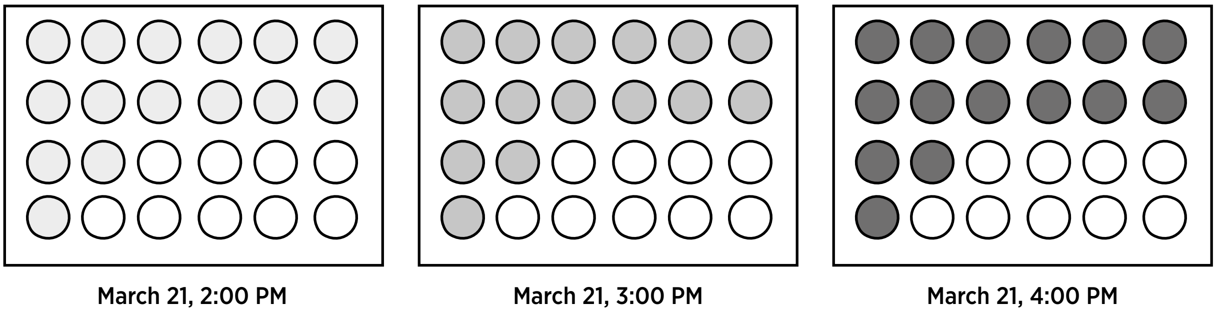
In addition, the shadowing effect from neighbouring buildings is calculated by simulating the sun's position over time. The model will test if a particular map cell is casting shadows onto other cells. A shadowing flag is raised for that particular cell at that particular point in time if shadowing is detected (Figure A2.3). The shadowing analysis is performed at various resolution levels to account for shadowing from terrain and from smaller objects. The calculation of shadows at every point produces hourly shadowing maps, similar to those presented in Figures A2.4 and A2.5. Boz, Calvert and Brownson (2015) and Gagnon et al. (2016) limit the computational requirements by selecting specific days, representative of a single month or season.

Figure A2.3: Illustration of the shadowing approach



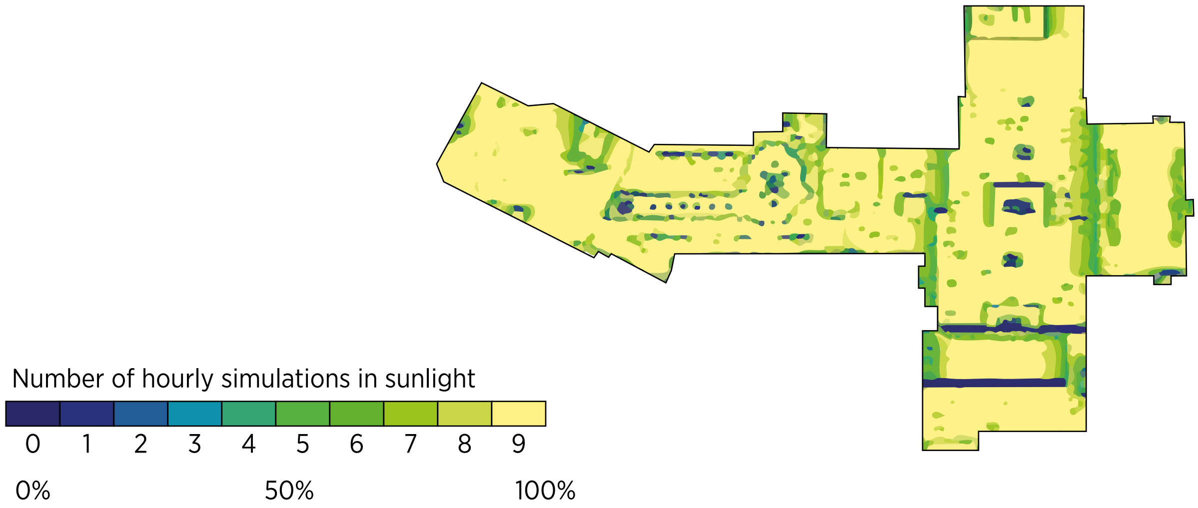
Note: The sun's position is simulated to assess if cell (b) is being shadowed by cell (a) at a given time.
Source: Lukač, N. et al. (2013), "Rating of roofs' surfaces regarding their solar potential and suitability for PV systems, based on LiDAR data", Applied Energy, Vol. 102, pp 803–12.

Figure A2.4: Example of hourly shading and sunlight availability



Source: Gagnon et al. (2016), "Rooftop solar photovoltaic technical potential in the United States: A detailed assessment", NREL/TP P-6A20-65298, *www.nrel.gov/docs/fy16osti/65298.pdf.*

Figure A2.5: Example of average daily hours of sunlight



Based on Gagnon et al. (2016), "Rooftop solar photovoltaic technical potential in the United States: A detailed assessment", NREL/TP P-6A20-65298, www.nrel.gov/docs/fy16osti/65298.pdf.

The shadowing from vegetation takes into consideration categories of canopies, either deciduous or coniferous. Deciduous vegetation drops its leaves during winter. A light absorption coefficient, varying between 0 and 1, is used to simulate the light absorption by the canopy.

At the exclusion of detailing the methodologies developed in the literature, it should be highlighted that calculating a solar cadastre requires a run of the solar irradiance models and the shading model for every rooftop at a time interval of 30 minutes to one hour over a period of one year.

Having calculated the solar irradiation, selecting the rooftop areas suitable for deployment is the final step in the process of estimating the potential. In practice, the most common constraints relate to the azimuth, the tilt of the rooftop surface. Complex decision points include:

» the definition of flat rooftops, as well as the optimal tilt angle that will be assigned to this category (the optimal angle will vary with latitude and is therefore city-dependent)

» PV system performance, usually ranging from 14% to 18%.

The total potential for the city is obtained by aggregating the values obtained for each rooftop. Practically, this would require extensive consultation with the final recipient of the modelling results since it is possible to change the perspective according to selected thresholds.

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