Delft University of Technology

Thesis

MSc Sustainable Energy Technology

Estimating the technical and economic potential of rooftop solar photovoltaics on Bali

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Abstract

The Indonesian aims to greatly increase the share of renewable energy sources in the electricity generation mix. Rooftop solar photovoltaics (RTSPV) are a potential generation method that can be used in support of this, with Bali chosen as a case study. No estimates of the total technical and economic potential of RTSPV on Bali exist in academic literature. Low spatial resolution statistical methodologies exist to estimate the technical potential of RTSPV, but these are not accurate on the sub-national scale of Bali. Methodologies with a medium spatial resolution are most suitable for an area of the scale of Bali, however existing methodologies cannot be used due to incomplete cadastral data. In this thesis a novel methodology is introduced that allows the use of incomplete cadastral data, in combination with land use data, to estimate the total rooftop area in a region at a medium spatial resolution. The total rooftop area is then used to estimate the total technical potential and the total economic potential. Using this method, the rooftop area of Bali is estimated to be 130 km^2, and the technical potential 22.9 TWh/year. The economic potential for RTSPV is estimated to be zero, as RTSPV cannot compete with conventional generation methods at current capital costs (CAPEX) of RTSPV components of 1200 USD/kWp. It is estimated that at a CAPEX of less than 870 USD/kWp sufficient electricity can be generated annually to fulfill the estimated annual demand of Bali of 5.7 TWh. 96% of the entire technical potential can be achieved at or below the cost per kWh of conventional generation methods if the price of RTSPV installations decreases to below 650 USD/kWp. If the compensation paid by the Indonesian state electricity company PLN for RTSPV electricity that is supplied to the grid is increased from 65% to 100% of the consumer electricity price, residential RTSPV installations can become economically viable at the current CAPEX of 1200 USD/kWp. This thesis will enrich existing literature on RTSPV potentials by introducing a novel methodology that can be applied in other regions with incomplete cadastral data. In addition, it provides a blueprint to estimate RTSPV potentials for other parts of Indonesia, and it supports policy makers by giving insight in factors that influence the economic potential of RTSPV on Bali and in Indonesia as a whole.

Acknowledgement

The master thesis you are about to read represents the culmination of the *exactly* nine years and one week I have spent as a student at the Delft University of Technology. It has been an interesting journey and I would like to thank my parents and DUO for standing beside me throughout all these years.

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List of abbreviations

BoS	Balance of Systems (all RTSPV components excluding PV modules)
BPP	Cost of electricity generation to PLN / price paid by PLN to IPPs for electricity
C_{gs}	PV Capacity of a grid square
CAPEX	Capital Expenses
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
FF	Fill Factor
GHI	Global Horizontal Irradiance
IEA	International Energy Agency
IESR	Institute for Essential Services Reform
IPP	Independent Power Producer
IRR	Internal Rate of Return
kWh	kilowatt hour (1000 watt hour)
kWp	Kilowatt peak (1000 watt peak)
LCOE	Levelized Cost of Electricity
MAE	Mean Absolute Error
NPV	Net present Value
OPEX	Operational Expenses
OSM	OpenStreetMap
P_{gs}	Technical potential of a grid square
PBP	Payback Period
PD_{PV}	Power Density of a PV module
PLN	Perusahaan Listrik Negara (Indonesian state electricity company)
PV out	Photovoltaic potential [kWh/kWp/year]
RA_{gs}	Rooftop area in a grid square
RAC methodology	Rooftop area calculation methodology
RMSE	Root Mean Square Error
ROI	Return on Investment
RTSPV	Rooftop Solar Photovoltaic
STC	Standard Test Conditions (1000 W/m^2, 298K)
SVF	Sky View Factor
TWh	Terawatt hour (10^{12} watt hour)
UF	Rooftop Utilization Factor

Contents

1 Introduction

The Indonesian government aims to increase the share of renewable electricity generation in the generation mix to 23% by 2025 and 31% by 2050 [1], up from 17% in 2020 [2]. Additionally, the state electricity company Perusahaan Listrik Negara (PLN) has pledged to become fully carbon neutral by 2060 [3]. Hydropower, geothermal, biomass, and wind energy make up the majority of the contribution of renewable energy in the electricity generation mix. Solar energy, however, makes a negligible contribution. Due to Indonesia's geographical location, the theoretical potential of solar energy is considerable. For example, an estimate by Langer et al [4] shows that enough electricity can be produced to cover 111% of Indonesia's 2018 electricity demand by using only 0.07% of Indonesian land area for utility scale solar photovoltaics. Rooftop solar photovoltaic (RTSPV) electricity generation is a subset of solar photovoltaic electricity generation. At around 4000 installations with a total capacity of under 30 MWp [5, 6], the overall contribution of solar photovoltaics in the energy mix in Indonesia is low. This low contribution is caused by a number of barriers present in the Indonesian electricity landscape. One important factor are the considerate government energy subsidies for many consumers, which make electricity cheaper than market price for most Indonesians. In addition, there is regulatory uncertainty around factors such as feed in tariffs and other subsidies on solar photovoltaics [7, 8, 9]. At the same time, RTSPV can play an important role in increasing the overall capacity of solar photovoltaics as the rooftops on which it is installed are currently rarely used for other purposes. For that reason RTSPV does not intrude on land areas that can be used for other applications, such as agriculture and nature reserves. The land use requirements of other common renewable energy technologies such as wind farms and utility scale solar installations can potentially cause such intrusions [10]. Globally, the market for RTSPV installations is steadily increasing, and it is expected to become responsible for 25% to 50% of overall solar photovoltaic electricity generation by 2050 [11] which makes its potential in specific localities a highly relevant research area. There is a larger body of academic research concerning the potential of solar photovoltaics in Indonesia [12, 13, 14, 15, 16, 17, 18, 19, 20], however, none of these explicitly focus on the potential of RTSPV electricity generation. A smaller, non academic body of research exists specifically regarding RTSPV potentials on Bali [21, 22], but these use statistical methodologies that cannot be verified.

This thesis aims to fill this gap by estimating the technical and economic potential of RTSPV with a higher degree of accuracy than what has been done in existing research. Bali has been chosen as a case study because of its geographical size, mix of urban and rural development and relatively developed grid. The size of Bali places it between the either large (country, continental) scale or small (city, building) scale of most existing research. In addition, Bali suffers from a lack of usable data that is necessary to accurately determine RTSPV potential such as cadastral data. Indonesia as a whole suffers from this deficiency, as well as many other developing countries. Existing methodologies require this spatial data to be complete in order to calculate total rooftop area, which is required to calculate overall technical potentials. In this thesis a methodology that is new in literature will be introduced that is computationally not intensive, and allows an accurate estimation of the total rooftop area to be made using incomplete cadastral data in combination with a built-up area density dataset with global coverage.

The aforementioned gaps in literature give rise to the following research question: What is the estimated technical and economic potential of rooftop solar photovoltaics on Bali, and how can these potentials be increased? This main research question will be answered through the following four research sub-questions:

1. What is the estimated total rooftop area on Bali?
2. What is the estimated technical potential of RTSPV on Bali?
3. What is the estimated economic potential of RTSPV on Bali?
4. How can the economic potential of RTSPV on Bali be increased?

The first step in answering the main research question is to estimate the total rooftop area on Bali in Section 5.1. This is achieved by employing a novel methodology, introduced in Section 3.2, which is validated in Section 4. Secondly, the potential annual yield — the technical potential — of solar panels installed on rooftops on Bali is calculated in Section 5.2. Rooftop geometry effects are accounted for in Section 5.2.1, and shading effects in Section 5.2.2, leading up to the estimation of the total technical potential of RTSPV on Bali in Section 5.2.3. In addition, a model to estimate the technical potential of individual rooftops is proposed in Section 5.2.4. The total economic potential in TWh/year is estimated in Section 5.3, with attention given to the LCOE of RTSPV in Section 5.3.2, and to the economic performance of individual RTSPV installations in Section 5.3.3. In addition, the parameters with the largest impact on the economic potential of RTSPV are identified, and policy options to increase the economic potential of RTSPV on Bali are discussed in Section 5.3.5. Lastly, the findings of this thesis are compared to other research in Section 5.4.

2 Literature review

2.1 On methodologies to calculate rooftop area, economic and technical potentials

A significant body of literature exists on the calculation or estimation of RTSPV potentials. The core of estimating RTSPV potentials is the estimation of total rooftop area suitable for RTSPV. To do this, a range of methodologies can be employed that vary in their scale — from building level to continental level — and in their spatial resolution. Methodologies can generally be classified in three categories [23]: low, medium and high level spatial resolution.

Low-level methodologies can establish a relationship between rooftop area and one or more other factors such as GDP, total population, population density, etc. through sampling [24, 25, 23, 12]. These functions are then applied to the target area. The International Energy Agency used a methodology to determine the total rooftop area as a function of population and population density that is applicable globally [13, 23], however Castellanos et al. [23] found a large degree of variance between the IEA model and more high-level studies of specific areas. Jacobson et al. [12] derived total building footprint areas for most countries in the world based on statistical information, including Indonesia.

Medium-level methodologies can be based on actual building footprint data in a region. This can be acquired from cadastral or GIS sources. Singh et al [26] and Bódis et al [27] apply land use data combined with GIS-based building footprint data to determine a ratio describing the actual building cover of a certain land use area. Horan et al [28] uses OpenStreetMap data of building footprints in combination with zoning GIS data to determine the total footprint area of commercial buildings in Dublin, Ireland. Both low-level and medium-level methodologies require an additional step to determine the fraction of usable rooftop area from building footprint or overall rooftop area as well as the overall photovoltaic potential in an area. This is can be found through sampling cadastral datasets or analysis of aerial photography and/or LiDAR data, depending on availability [29].

High-level methodologies use complete datasets for rooftop characteristics of a target area. Essentially, all buildings and their roofs are digitized, and optimal RTSPV installations are generated per building [23][29]. These methodologies are the most accurate but require complete and detailed data on building characteristics and they are highly computationally intensive. This data might not always be available for the area of interest, and sufficient computational capacity might not always be available either.

The medium and high level methods described above utilize existing data on building footprints and rooftop characteristics. Data availability has a high impact on the methods used: only if detailed data on rooftop characteristics is available for a certain area, high-level methods can be applied. Alternatively, machine learning algorithms have been employed to distill useful data from secondary sources that was not otherwise available [29]. Machine learning methods on their own are not a low, medium or high-level methodology, but an alternative data processing technique that can fit into any of the three levels, depending on the application. Joshi et al [30] have used machine learning algorithms to determine usable rooftop areas from satellite images. There are also commercial firms such as Solar AI that offer detailed assessment of rooftops using machine learning and imagery [31]. None of the methodologies discussed allow for calculating total rooftop area and consequently technical and economic potentials of RTSPV with incomplete spatial data on the scale of Bali. Existing low, medium and high level approaches all require complete spatial data. Employing machine learning algorithms on complete satellite imagery of Bali would theoretically be possible, but these approaches are too computationally intensive to use on the scale of Bali [29]. This represents a gap in existing literature, which the methodology that is introduced in this thesis aims to fill.

2.2 On the technical and economic potential of rooftop solar PV on Bali

The potential for RTSPV on Bali has been recognized and has been given some attention, especially by the Indonesian Institute of Essential Services Reform (IESR). One report [21] found that the market potential of rooftop PV in 34 provinces is between 48.6 and 163.6 TWh. The technological potential that was found was significantly higher, at 275.8 to 930.7 TWh for all 34 provinces. For reference: total electricity consumption in Indonesia in 2019 was 271 TWh [2]. This research paper uses a low-level spatial approach that calculates rooftop area by multiplying average household floor space statistics by the number of households in the target area, which is a low level spatial methodology. Another IESR publication, specifically on the rooftop PV potential in Bali, states a total potential capacity for rooftop PV of 41.3 MWp [22], which could generate 62 GWh/year when assuming an average PV potential of 1500 kWh/kWp/year. However, no underlying data or methodology is provided.

A few publications concerning RTSPV on Bali or in Indonesia as a whole exist, but these publications do not focus specifically on its technical and economic potential. A market survey on the willingness to adopt rooftop PV by households and businesses was conducted by the IESR, specifically for Bali [32]. The outcome of this survey was that the majority of people and businesses are willing to adopt rooftop PV, with their main objectives being 1) saving on electricity expenses and 2) to be less susceptible to PLN outages. A majority desired a payback period of less than 5 years on the initial investment. Market research on the perceptions toward RTSPV in Indonesia as a whole by Setyawati [9] show that potential customers are sensitive to the high capital costs of RTSPV systems, as well as the long payback period. An additional barrier was found in the fact that PLN only pays 65% of the consumer electricity price in return for electricity supplied to the grid by RTSPV installations. This return was determined to be too little to allow residential RTSPV installations to be economically viable [9]. Putrano et al. [6] has conducted research on the trend of RTSPV LCOE and its progress towards achieving grid parity. The definition of grid parity is that the LCOE of RTSPV is lower than a certain price related to the cost of electricity. Putrano et al. define three phases of grid parity, with the first phase being when the LCOE of RTSPV is lower than the consumer price of electricity. The second phase is when the LCOE is lower than the industrial (commercial) electricity price, and the third phases is when the LCOE is lower than the cost of generating electricity by conventional means [6]. Putrano et al. conclude that RTSPV is on the cusp of achieving the first phase of grid parity in Jakarta. In conclusion, some studies exist that estimate the technical potential of RTSPV on Bali, but they use low-level spatial resolution methodologies. No studies exist that estimate the economic potential of RTSPV on Bali, which refers to the amount of electricity that can be economically generated by RTSPV. This thesis aims to fill this research gap.

3 Methodology

In this chapter, the methodology used in this research is described. In Section 3.1 the main data sources used are introduced. In Section 3.2 a novel methodology is introduced by which the total rooftop area on Bali is approximated. This methodology is validated in Chapter **??**The methodology used to calculate the technical potential of RTSPV on Bali is described in Section 3.4. Finally, the methodology used to assess the economic potential of RTSPV on Bali is described in Section 3.5.

3.1 Data used

To calculate the total rooftop area on Bali two data sources are used: a global land cover map of Bali of the Copernicus Global Land Service [33], and building footprint data for Bali from OpenStreetMap (OSM) (Figure 1). From the Copernicus land cover database, the built-up area data is used. This data consists of 431287 100m x 100m grid squares with an associated built-up area density from 0 to 100% that cover all of Bali. The built-up area data set has a mean absolute error (MAE) of 1.5% and a root mean square error (RMSE) of 7.9% in the region containing Bali. This accuracy is comparable to that found in the rest of the world [34]. The built-up area density data does not contain any information regarding the actual building footprint area of the buildings contained in each grid square. For this reason another data source is required which contains building footprint data. This data source is the building footprint area data from OSM.

(a) (b)

Figure 1: Complete OSM map of an area in Denpasar, Bali (a), and the isolated building footprint polygons (b).

Since the OSM building footprint data will be used as the basis to calculate total building footprint area, any inaccuracies in the OSM data will propagate to the final building footprint area calculated. When complete sections — being sections where OSM building footprint data is visually confirmed to be present for all buildings — of the OSM data on Bali are compared to satellite imagery, it appears that the actual building footprint area is approximately 25% higher than what is represented by the OSM data (see Appendix A). The methodology to calculate building footprint area, which will be introduced in Section 3.2, will use the OSM building footprint area. As a consequence, the actual building footprint area on Bali can potentially be 25% higher than the total building footprint area that will be calculated in Section 5.1. The OSM building footprint dataset, together with the Copernicus built-up area dataset, is divided into 22 sectors covering all of Bali. Of these 22 sectors, 4 have been omitted due to almost entirely missing OSM building footprint data in these sectors (Figure 2). The omitted sectors amount to approximately 9% of the total area of Bali

For the purpose of calculating the potential annual electricity yield of Bali rooftops two additional data sources are used. Solar irradiation data — Direct Normal Irradiance, Diffuse Horizontal Irradiance, sun azimuth and attitude — and weather data — wind speed, ambient temperature — for Denpasar are obtained from Meteonorm version 7.3.4. Meteonorm includes the option to generate weather data based on historical weather, or based on an estimation of future weather. For this research, historical weather data is used. The Meteonorm weather data will be used for the calculation of the effects of rooftop geometry and shading in Sections 5.2.1 and 5.2.2. However, Meteonorm weather data is only available for Denpasar. Since solar irradiance varies across Bali, solar irradiance data with a higher resolution is preferable for determining the total technical and economic potentials of RTSPV across Bali. For this purpose the solar power potential dataset from Solargis[35] is better suited. This dataset has a resolution of 250m x 250m and provides annual solar photovoltaic potential per kWp of installed capacity in kWh/kWp/year. This parameter is also referred to as PV out or PV potential in this thesis. In literature it can also be referred to as the specific yield parameter. The map of Bali based on the Solargis dataset is depicted in Figure 3. The range of deviation of the Solargis irradiance data on which the photovoltaic potential dataset is based is $\pm 8\%$ at a P90 uncertainty [36].

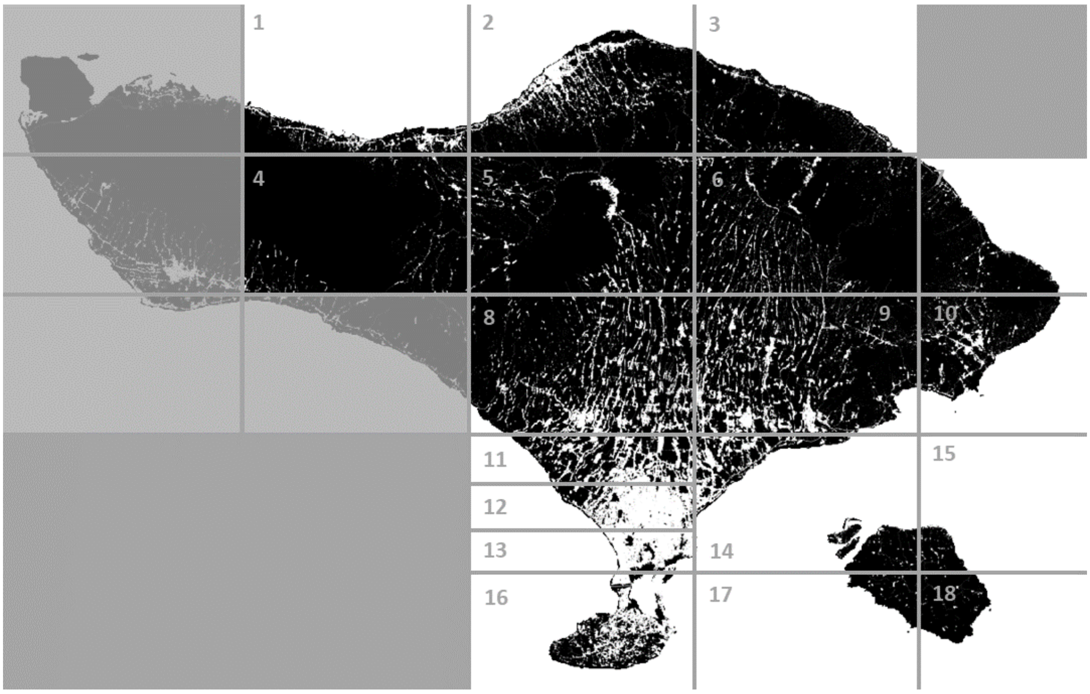

Figure 2: Overview of the sector division of Bali. Sectors marked grey have been omitted due to OSM data being almost completely missing.

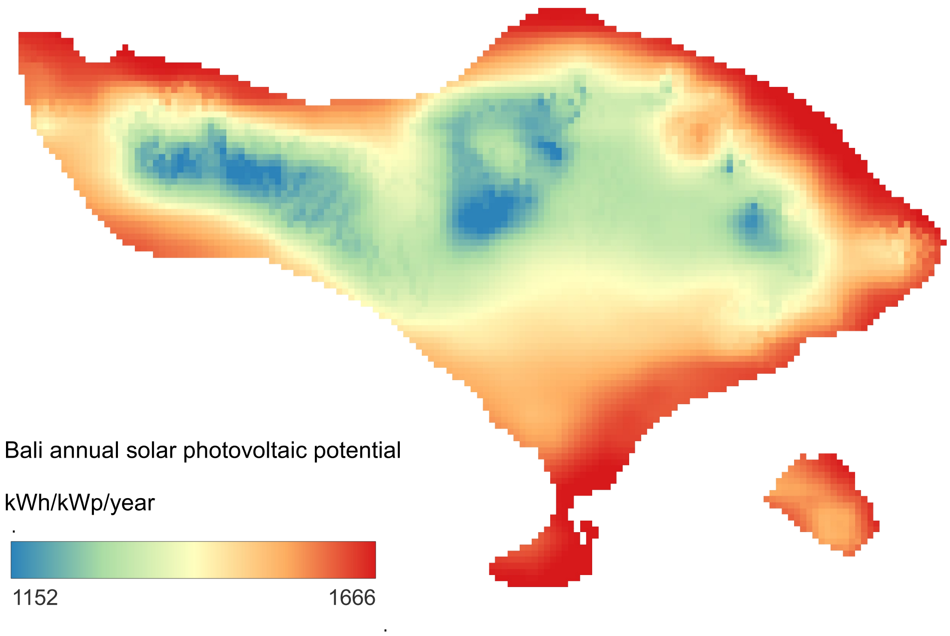

Figure 3: Bali annual solar photovoltaic potential (PV out) map. Source: Solargis.

Parameter	Description
Description	Built-up area density percentage map
Creator	Copernicus Global Land Operations "Vegetation and Energy"
Publisher	Copernicus Global Land Service
Spatial range	$100°$ E to $120°$ E and $0°$ to $-20°$ N
Spatial resolution	100m x 100m
Dataset	E100N00_PROBAV_LC100_Global_v3.0.1_2019-nrt_BuiltUp_CoverFraction-layer_EPSG-4326
Data type	Raster
Parameter unit	%
Time period	2019
Description	Building footprint area map
Creator	Open source
Publisher	OpenStreetMap
Spatial range	Province of Bali
Spatial resolution	Approximately 1m
Data point	Building footprint shape and location
Data type	Vector
Parameter unit	Meter
Time period	2022
Description	Denpasar weather data
Creator	Meteonorm version 7.3.4
Publisher	Meteonorm
Location	Denpasar, Bali
Data points [unit]	DNI [Wh/yr], DHI [Wh/yr], solar azimuth and attitude [deg], wind speed [m/s], ambient temperature [°C]
Data type	Hourly data for an entire year
Time period	2005-2015
Description	Bali localized annual PV potential (PV out) long term average
Creator	Solargis
Publisher	World Bank Group
Location	Indonesia
Spatial resolution	250m x 250m
Data point	Indonesia_GISdata_LTAym_YearlyMonthlyTotals_GlobalSolarAtlas-v2_GEOTIFF
Data type	Raster
Parameter Unit	kWh/kWp/yr
Time Period	2007-2018

Table 1: Metadata of datasets used in this thesis.

3.2 Total rooftop area estimation

The methodology that will be introduced in this section allows the use of incomplete OSM data, combined with complete built-up area data to estimate actual total building footprint area in a specific region. This building footprint area is then assumed to be equal to the total rooftop area in that region. The first step of this methodology is to overlay the OSM building footprint map with the Copernicus built-up area map, as depicted in Figure 4. The grayscale squares represent the 100m x 100m grid squares of the built-up area map, and the yellow polygons represent the building footprint map. White 100m x 100m grid squares indicate areas with 100% built-up area density, while black squares indicate areas that are not built-up. Darker shades of grey indicate a lower built-up area density, and lighter shades a higher density. The red box marks an area that should be built up according to the built-up area map, but with most building footprints missing. This indicates incomplete OSM data in that area. While part of all of grid squares with incomplete building footprint data can have building footprint data missing entirely, the remaining incomplete grid squares can contain some but not all building footprints. These grid squares will be referred to as 'underfull'.

Figure 4: The OSM building footprint map (highlighted yellow) overlaid with the Copernicus built-up area map (grayscale). The grayscale blocks represent the built-up area data grid squares of 100m x 100m. The red box indicates an area that should be built up according to the Copernicus built-up area map, but with many mapped OSM building footprints absent. This indicates incomplete OSM data in that area.

The working principle of the rooftop area calculation (RAC) methodology is the construction of a discrete function that describes the building footprint area associated with the built-up area density percentage point of every 100m x 100m grid square. If this function is then applied to all grid squares on Bali, the total building footprint area, and consequentially the total rooftop area on Bali can be approximated. A schematic of the RAC methodology is given in Figure 5. The first step is the merging of the built-up area density map of the target area from Copernicus — which consists of 100m x 100m grid squares with an associated built-up area density — with the building footprint map of the target area from OSM. In the case of Bali, this results in 431287 data points, each data point containing for a grid square the built-up area density, the area, and the building footprint area contained in that grid square. The second step is the removal of grid squares with incomplete OSM building footprint data. This is achieved with a simple threshold filter that removes all grid squares with a nonzero built-up area density, but with zero building footprint area contained in it. The reasoning behind this is that if there are no buildings mapped in OSM in areas that should be built-up according to the built-up area map, the OSM data can be assumed to be missing. There is a caveat to this assumption, as there are cases where areas are built-up but do rightfully not contain any buildings, such as roads, parks, squares, etc. This caveat will be revisited in section 4. What remains is a dataset containing all grid squares with zero built-up area density and their associated building footprint areas (some grid squares with 0% built-up area density will have a small number of buildings nevertheless), and all grid squares with nonzero built-up area densities and nonzero building footprint areas. From this dataset the average building footprint area of all grid squares for each percentage point of built-up area density is then calculated in step three. Step four serves to remove underfull grid squares, which are grid squares that contain less than 20% of the average building footprint area that they should contain given their built-up area density percentage point. The 20% threshold is established empirically in Section 4.4. The average building footprint area per percentage point of built-up area density [Figure 6] is then re-calculated with the remaining grid squares in step five. This function is then applied to all grid squares in the target area, including the grid squares removed in steps two and four, in step six. This is done by summing the average building footprint area associated with every grid square based on the built-up area density of that grid square. Finally, this results in an approximation of the building footprint area contained in the target area. The rooftop area calculation methodology introduced in this section has not been found in literature, and is therefore novel.

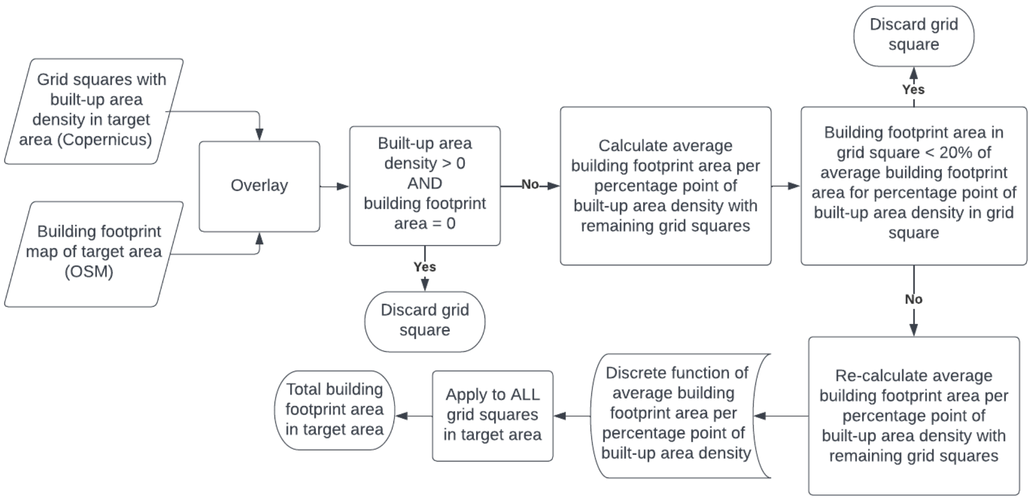

Figure 5: Schematic of the rooftop area calculation methodology.

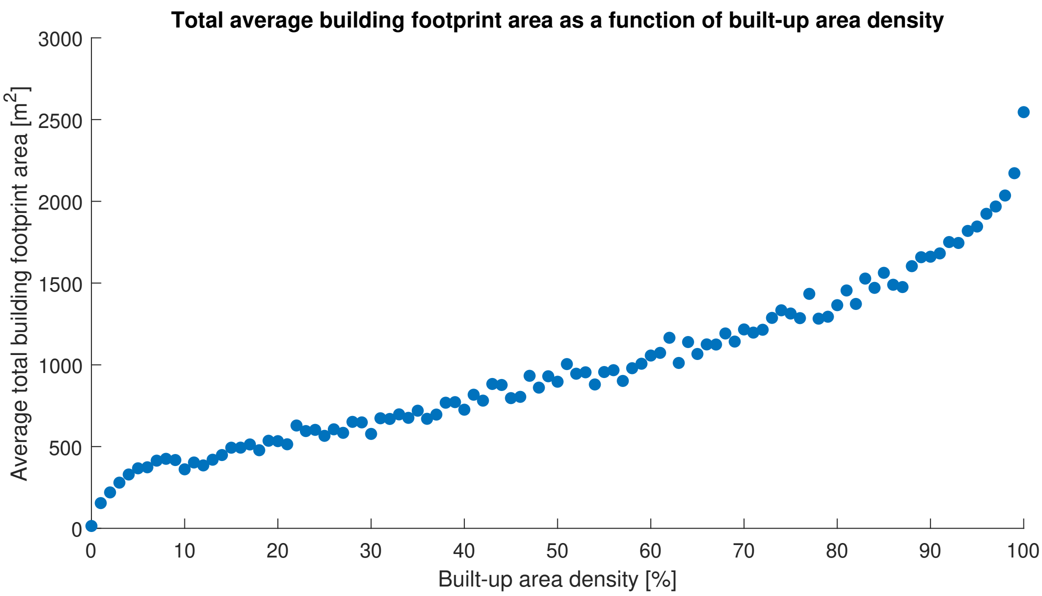

Figure 6: Plot of the average building footprint area associated with each percentage point of built-up area density.

3.3 Validation of rooftop area calculation methodology

Since the RAC methodology is new and untested, it needs to be validated for accuracy. This is done by means of four different approaches. First, the RAC methodology is tested for convergence for increasing sample sizes. If the calculated rooftop area converges to a single value, the RAC methodology is assumed to be convergent.

Second, the RAC methodology is applied to 11 areas (validation sectors) in Western Europe and North America, where the OSM data is complete [37]. Since the OSM data is complete, the actual total building footprint area in each validation sector is known. The building footprint area that is calculated by applying the RAC methodology can then be compared to the actual building footprint area. The degree by which the calculated building footprint area exceeds the actual building footprint area is referred to as the 'overshoot factor'. Three other parameters will be calculated for each validation sector: the 'fullness factor', referring to the share of grid squares with nonzero built-up area density that actually contain buildings, the maximum building footprint area, referring to the building footprint area associated with 100% built-up area density, and the average built-up area density. The overshoot of each validation sector will be correlated with each of the three other parameters in order to identify a correlation between the degree of overshoot and the magnitude of the fullness factor, the maximum building footprint area or the average built-up area density.

Third, the variance of all building footprint areas associated with each percentage point of built-up area density will be assessed. The purpose of this is to investigate whether a higher variance has a negative impact on the accuracy of the rooftop area calculated with the RAC methodology. As explained in Section 3.2, the RAC methodology works by averaging all nonzero building footprint areas contained in all grid squares with a specific percentage point of built-up area density. There are essentially 101 datasets with building footprint areas: one for each percentage point of built-up area density. In other words: each percentage point of built-up area density has a range of building footprint areas associated with it. Each dataset contains all the building footprint areas of grid squares with that specific built-up area density percentage point. Of each dataset, the variance can be calculated. The variance describes the dispersion of all data points — in this case building footprints — contained in a dataset [38]. If the variance is low, the data points are grouped close together. If, on the other hand, the variance is high, there is a larger spread in the building footprint areas of the grid squares of a certain percentage point. All 101 variances of the complete building footprint area dataset for a validation region can be plotted in a scatter plot, as is done for five validation sectors and Bali in Figure 15. The variance essentially describes the connection between building footprint area and built-up area density. If the variance of a dataset is low, there should be a stronger connection between building footprint area and built-up area density than when the variance is high. It could be possible that a validation region with higher variance for all its data points produces less accurate results when the RAC method is applied to it. This hypothesis will be tested in Section 4.3.

Fourth, the RAC methodology will be applied to validation sectors where parts of the OSM building footprint data have been manually removed. By manually cutting out sections of the building footprint map, the manifestation of missing data on Bali is approximated. If 'holes' are cut into the building footprint map of a validation sector, not only will a part of the data be simply removed, a number of 'underfull' grid squares will also be created. Underfull grid squares are grid squares where part of the building footprints, but not all, are missing. These grid squares will therefore contain less building footprint area than they should, but they will not be removed by the first filtering step as described in Section 3.2. This can potentially lead to a lower average building footprint area associated with each percentage point of built-up area density, and therefore a lower calculated built-up area density. This will be explored in Section 4.4. Additionally, a way to eliminate this effect through applying a second filter — as mentioned in Section 3.2 — will be developed.

3.4 Estimation of technical potential of RTSPV

In this section, the methodologies used to estimate the technical potential of RTSPV on Bali are introduced. Section 3.4.1 a methodology is described that provides a baseline estimation for the total technical potential of RTSPV on Bali. In Sections 3.4.2 and 5.2.2 methodologies to refine the baseline technical potential estimation in relation to rooftop geometry and shading are introduced.

3.4.1 Baseline technical potential

In Section 2 methodologies used to calculate technical potentials of RTSPV were divided into three categories: low, medium and high level. Given the data available on Bali, a medium level methodology can be developed that is based on the Copernicus built-up area density, the OSM building footprint area, and the Solargis solar power potential datasets. As part of the RAC methodology introduced in Section 3.2, a dataset is created of the estimated total rooftop area contained in each 100m x 100m grid square. By overlaying the Solargis solar power potential dataset the total solar power potential of each grid square can be determined. The potential RTSPV capacity of a grid square C_{gs} is calculated in Equation 1, with RA_{gs} the total rooftop area in the grid square, UF the rooftop utilization factor (the share of each rooftop covered with solar modules), and PD_{pv} the power density of the solar module in kWp/m^2. The representative solar module that will be used in this thesis is the SunPower X22-370. By multiplying C_{gs} by the solar power potential PV_{out} in Equation 2, the total RTSPV potential in kWh/year is calculated. Equation 2 can be applied to any size RTSVP installation. Additionally, by dividing both sides of Equation 2 by the capacity C_{gs} the PV_{out} of an RTSPV installation can be calculated when its total capacity and annual yield are known, resulting in Equation 3 which can again be applied to any RTSPV installation.

$$C_{gs} = RA_{gs} * UF * PD_{pv} \tag{1}$$

$$P_{gs} = C_{gs} * PV_{out} \tag{2}$$

$$PV_{out} = \frac{P}{C} \tag{3}$$

This approach will give an approximation of the actual technical potential of RTSPV on Bali. It should, however, be noted that it does simplify a number of factors, specifically rooftop geometry and shading by surrounding objects. The Solargis solar power potential dataset only contains the solar power potential of horizontal surfaces. If the majority of roofs is not horizontal, the consequences for the total technical potential are unknown. Accurately determining the impact of roof geometry and shading can be done by employing a more high-level methodology. High-level methodologies are based on the modeling of individual rooftops and their surroundings in an area of interest, with optimized RTSPV panel arrays installed on every rooftop. These methods are the most accurate, but not applicable to Bali due to a lack of rooftop geometry data availability. However, the building methods used in Indonesia allow a hybridized method, which is introduced in Section 3.4.2.

3.4.2 Rooftop geometry effects

As can be seen in Figure 7, there is a high degree of similarity between roofs. The vast majority of roofs are hip roofs with segments angled at approximately $30°$. In this section a methodology is introduced that can be used to 1) estimate the effect of roof geometries on the total technical potential of RTSPV on Bali, and 2) estimate the performance of an RTSPV module on an individual roof based on the rooftop geometry.

Central to this model lies the calculation of the total irradiance on a solar panel module on a rooftop with a specific orienatation (G_M) at a specific time. This is calculated using Equations 4-7 [39, 40], the parameters of which are defined in Table 2. In order to calculate annual irradiance, this calculation has to be made for all 8760 hours in a year, assuming an hourly resolution. For these calculations, Meteonorm data for an entire year with an hourly resolution is used.

$$G_M^{dir} = DNI * cos\gamma * Shading \tag{4}$$

$$G_M^{dif} = DHI * SVF \tag{5}$$

$$G_M^{ref} = GHI * \alpha * (1 - SVF) \tag{6}$$

$$G_M = G_M^{dir} + G_M^{dif} + G_M^{ref} \tag{7}$$

In Equation 4, Shading refers to a boolean factor — meaning the shading factor is either 0 or 1 — describing the shading of a solar module at a specific time of day. The Shading, SVF and α factors are location dependent and require local measurements to determine accurately. This data is not available for Bali. Calcabrini et al [40] proposes a simplified methodology that does not require this high volume of calculations. In Section 5.2.2 a shading model is proposed that is based on their methodology.

Using Equations 4-7, together with hourly data for solar position (azimuth and attitude) and irradiance (DNI and DHI) from Meteonorm the annual irradiance on a rooftop on Bali can be calculated. With the aforementioned solar radiation data, ambient temperature and wind speed (also taken from Meteonorm), a temperature model is constructed based on an example provided in the PV_LIB documentation[41] using the PV Performance Modeling Collaborative PVLIB toolbox for Matlab [42]. With these irradiance and temperature functions, coupled with a rooftop utilization factor and a Balance of System efficiency — being the efficiency of all other parts of the RTSPV installation such as the inverter — of 0.91, a set of formulas can be constructed that describe annual RTSPV yield for an RTSPV installation based on its size, orientation and tilt.

The power output of an individual solar module P_m is calculated with Equations 4-7, and the additional Equations 8-11. The parameters of the equations are defined in Table 2.

$$T_m = 273 + (G_m \exp{(a + bWS)} + T_{ambient})[42] \tag{8}$$

$$V_{oc} = (V_{oc}(STC) + \frac{nk_bT_m}{q}\ln(\frac{G_m}{G_{STC}}))(1 + T_{Voc}(T_{module} - 298))[39] \tag{9}$$

$$I_{sc} = I_{sc}(STC)\frac{G_M}{G_{STC}}(1 + T_{Istc}(T_m - 298))[39] \tag{10}$$

$$P_m = V_{oc}I_{sc}FF\eta_{bos} \tag{11}$$

In order to simulate the effect of roof tilt on the total technical potential of Bali, the entire rooftop area of Bali can be assumed to be a singular roof segment under a specific tilt. First, the assumption is made that due to the large amount of buildings on Bali, the azimuth — or rotation from due north — of all roofs is homogeneously distributed between $0°$ and $359°$. Using that assumption, the irradiance on a tilted roof can be calculated by first simulating the annual irradiance on that rooftop using hourly weather data for each degree of azimuth and then calculating the average annual irradiance of these 360 simulations. If the tilt of the roof is set at $0°$, the annual irradiance on a horizontal roof is calculated. The result of this calculation is a formula for the total technical potential of RTSPV on Bali as a function of rooftop tilt.

Figure 7: Aerial photograph of a neighbourhood in Denpasar, Bali. Source: Google Maps

Description of parameters used in Equations 4-11		
Parameter	Description	Unit
G_M	Total irradiance on solar module	W/M^2
G_M^{dir}	Direct irradiance on solar module	W/M^2
G_M^{diff}	Diffuse irradiance on solar module	W/M^2
G_M^{ref}	Reflected irradiance on solar module	W/M^2
DNI	Direct Normal Irradiance	W/M^2
DHI	Diffuse Horizontal Irradiance	W/M^2
GHI	Global Horizontal Irradiance	W/M^2
γ	Angle of incidence of DNI on solar module	degrees
SVF	Sky View Factor	-
α	Albedo (reflectivity of surroundings)	-
T_m	Solar module temperature	K
a	Solar module mounting parameter	-
b	Solar module mounting parameter	-
WS	Wind Speed	m/s
$T_{ambient}$	Ambient temperature	K
V_{oc}	Open circuit voltage	V
I_{sc}	Short circuit current	I
STC	Standard Test Conditions (1000W/M^2, $298K$)	-
n	ideality factor	-
k_b	Bolzmann constant	J/K
q	Elementary charge	C
G_{STC}	Module irradiance under STC	W/M^2
T_{Voc}	Voltage temperature coefficient	mV/K
T_{Isc}	Current temperature coefficient	mA/K
P_m	Power output of RTSPV module	W
FF	Fill Factor	-
η_{bos}	Balance of Systems efficiency	%

Table 2: Overview of parameters used in Equations aadsffasd-8

3.4.3 Shading effects

Shading is entirely dependent on the location of a rooftop and its surroundings, and it therefore requires detailed local data to calculate. This data is not available for all the buildings on Bali. However, it is possible to construct a simplified model. Calcabrini et al. [40] proposes a model that uses the sky view factor and a sun coverage factor to calculate annual irradiation on a specific photovoltaic system. This approach still requires some local data. In this section a methodology is proposed to calculate the effect of an obstruction that blocks all diffuse and direct irradiance below a specific degree of attitude across all 360 degrees of azimuth. This model is too simplified to accurately calculate the effects of specific obstructions around individual rooftops, but it does give insight in the sensitivity of overall electricity yield to obstructions. A central assumption is that shading only results from obstructions around the RTSPV installation, and not from mutual shading between individual solar modules. The reasoning is that the favourable geographic location of Bali allows for the installation of solar modules parallel to the rooftop surface without causing a negative effect on overall yield. For this reason, individual modules do not need to be angled, and will therefore not cause shading on other modules. This means that this model is only applicable for RTSPV installations where the solar modules are not obstructed in any way by neighbouring solar modules. The model proposed here calculates the effect of a homogeneous obstruction blocking direct normal irradiance and diffuse horizontal irradiance below a specific attitude a_{block} across all 360 degrees of azimuth. The effect of a_{block} on DNI is calculated by means of a Boolean function which sets the DNI at solar attitude a_{sun} to 0 if $a_{sun} < a_{block}$ in Equation 12.

$$DNI(a_{sun}) = \begin{cases} 0, & \text{if } a_{sun} < a_{block} \\ DNI(a_{sun}), & \text{if } a_{sun} => a_{block} \end{cases} \quad (12)$$

The effect of the obstruction caused by a_{block} on G_M^{dif} is calculated by calculating the SVF_{block} as a function of a_{block}. The blue cone in Figure 8 represents the fraction of the celestial sphere visible to a point M on a solar module as a consequence of a_{block}. The area of the sector A_{sector} is calculated with Equation 13. The SVF_{block} is then equal to the fraction of area of the hemisphere covered by the area of the sector in Equation 14. By means of Equations 12 and 15 a simplified shading model can be made to assess the sensitivity of solar yield to certain amounts of shading.

$$A_{sector} = 2\pi rh = 2\pi r^2(1 - sin(a_{block})) \quad (13)$$

$$SVF_{block} = \frac{A_{sector}}{A_{hemisphere}} = 1 - sin(a_{block}) \quad (14)$$

$$G_M^{dif} = DHI * SVF_{block} \quad (15)$$

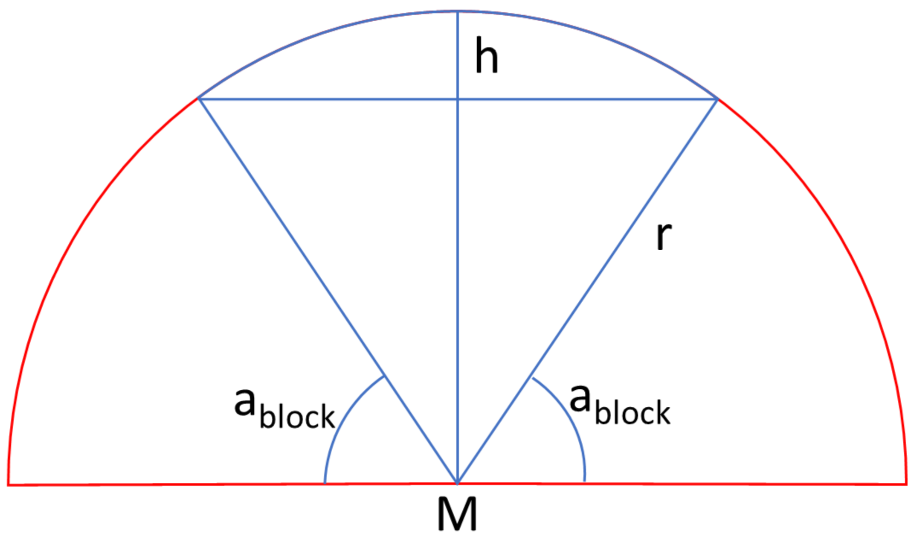

Figure 8: 2D representation of a sector of a hemisphere

3.5 Economic potential

For assessing the economic potential of RTSPV the levelized cost of electricity (LCOE) — defined by Equation 16 [39] — can be used [43, 27, 6]. Calculating the LCOE for RTSPV allows for a comparison with prices for grid electricity. A key economic milestone for RTSPV on Bali is reaching grid parity, meaning that RTSPV electricity costs the same to generate as the price PLN pays for electricity. This price is referred to as the BPP, and is equal to 0.0623 USD/kWh as of 2020[44]. However, RTSPV can be employed directly by consumers, who pay a different price for electricity, namely 0.1 USD/kWh [45] as of 2020. Electricity prices for commercial customers vary between approximately 0.065 USD/kWh and 0.075 USD/kWh [45]. As RTSPV electricity can directly replace electricity that is otherwise purchased from the grid by the consumer, it is also relevant to compare the LCOE of RTSPV to the consumer and commercial electricity price rather than the BPP. Putrano et al. [6] recognize this and define different levels of grid parity, based on when the LCOE of RTSPV matches different electricity prices. In this research three levels will be used: the BPP of 0.063 USD/kWh, the high commercial electricity price of 0.075 USD/kWh, and the consumer electricity price of 0.1 USD/kWh.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Yield_t}{(1+r)^t}} \quad (16)$$

$CAPEX_t$ refers to the investment costs for the RTSPV installation in year t, $OPEX_t$ refers to the annual maintenance costs of the installation, $Yield_t$ refers to the annual electricity yield of the installation in kWh/year. The CAPEX is applied in year 0 — meaning the CAPEX is not discounted — and OPEX and annual yield are applied from year 1 onward. The annual discount rate is represented by r, and n is the number of years considered for the LCOE calculation, assumed to be equal to the generally expected lifetime of an RTSPV installation of 20 years [39]. A reduction in solar module efficiency due to degradation is ignored, as the SunPower X22-370 retains approximately 96% of its efficiency after 20 years. CAPEX, maintenance and annual yield all vary based on RTSPV system size and location, and consequentially their LCOE varies as well. For this reason, LCOE is a useful factor to assess the economic potential of different sizes of RTSPV installations on Bali.

Total economic potential of RTSPV expressed in TWh/year as a function of CAPEX and PV potential can also be calculated using Equation 13, in combination with the Copernicus built-up area data and the RAC methodology introduced in Section 3.2, and localized PV potential data from Solargis[35]. Since $CAPEX_t$, $OPEX_t$ and $Yield_t$ are all assumed to be linear functions of the total capacity in kWp of the RTSPV installation, the LCOE is independent of the total capacity, and the LCOE can be calculated as a function of PV potential rather than $Yield_t$. This allows Equation 13 to be adapted to calculate the required PV potential to generate electricity at a specific LCOE, assuming a specific CAPEX and OPEX per kWp. The number of grid squares that receive sufficient irradiance to generate at minimum that required PV potential can be determined using the dataset constructed in Section 3.4.1. The sum of the total annual yield of those grid squares then represents an estimate for the total economic potential of RTSPV at that LCOE in TWh/year.

The LCOE provides valuable insight in the economic potential of RTSPV under current and hypothetical economic circumstances. However, while the cost of RTSPV is equal to the LCOE, the value is not by definition equal to its cost. This is because of the fact that the reimbursement for electricity that is exported to the grid is limited to 65% [9] (the 'refund factor') of the electricity price. As a consequence, the fact that the LCOE might be low enough to compete with other sources of electricity does not guarantee that an RTSPV installation can be actually profitable. In order to assess the economics of RTSPV on Bali in practice, return on investment (ROI) (Equation 17), net present value (NPV) (Equation 19) [46], payback period (PBP) (Equation 18), and the internal rate of return (IRR) are used. The formula for the IRR is not given here, as it is the discount rate associated with an NPV of zero. For that reason, it has to be calculated iteratively using the formula for the NPV.

$$ROI = \frac{\textit{Annual income}}{\textit{CAPEX}} * 100\% \tag{17}$$

$$PBP = \frac{1}{ROI} \tag{18}$$

$$NPV(i,n) = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{19}$$

For Equation 19, i represents the discount rate, n the number of years over which the NPV is calculated, and R_t the cash flow in year t. As the price paid by PLN to consumers is only 65% of the electricity price they pay for grid electricity, the total costs that are avoided by installing an RTSPV installation depend on the share of generated electricity that is immediately consumed, instead of supplied to the grid. This is referred to as 'self consumption'. The self consumption can only be calculated if RTSPV generation and consumer electricity demand profiles are known. A model RTSPV demand profile is generated as part of the technical potential calculation. A representative demand profile for a household on Bali is not available on literature, but is estimated based on typical appliances in a household and when they are used in Appendix B. The hourly demand and generation profiles for a year for a given RTSPV installation and consumer are then summed. Any electricity drawn from the grid is multiplied by the electricity price, and any electricity supplied to the grid is multiplied by 65% of the electricity price. The avoided costs R_{AC} — being grid electricity costs avoided by a consumer by generating their own electricity through RTSPV — can be calculated with Equation 20, where SC refers to the rate of self consumption and P to the applicable electricity price. The self consumption is the share of generated electricity that is immediately consumed by the consumer. Income from RTSPV electricity sales to the grid (R_{GS}) are calculated with Equation 21, where RF represents the refund factor, which is currently 65% in Indonesia. Lastly, the total income R_{total} is calculated in Equation 22.

$$R_{AC} = Yield_{annual} * SC * P \tag{20}$$

$$R_{GS} = Yield_{annual} * (1 - SC) * RF * P \tag{21}$$

$$R_{total} = R_{AC} + R_{GS} \tag{22}$$

4 Validation

In order to confirm the accuracy of the rooftop area calculation (RAC) methodology that was introduced in Section 3.2, the calculated rooftop area in a region should be confirmed with the actual rooftop area in that region. However, no complete rooftop area data exists for Bali. This fact requires that the rooftop area calculation methodology is validated by alternative methods. This validation process is discussed in this chapter. The first check performed on the RAC methodology is on its convergence towards a stable outcome for increasing sample size in Section 4.1. If the RAC methodology is not convergent, the resulting building footprint area cannot be reliable. Secondly, the RAC methodology will be applied to 11 sample validation areas in regions with complete building footprint data in Section 4.2 for the purpose of comparing the building footprint calculated with the RAC methodology to the actual building footprint area in each sample area. Thirdly, the variance in the datasets generated for the validation areas will be assessed to exclude a correlation between higher variance and less accurate results in Section 4.3. Fourth, to assess the effect of incomplete building footprint data as found on Bali, the building footprint data in a validation area will be made artificially incomplete, and the RAC methodology will be applied to it in Section 4.4. Finally, the conclusions of the validation process will be summarized in Section 4.5.

4.1 Convergence

The convergence will be assessed first. As discussed in Section 3.1, the OSM building footprint data and Copernicus built-up area density data have been divided into 18 sectors. The convergence is assessed by calculating the total building footprint area on Bali based on progressively more sectors. Iteration 1 is based on only one sector, while iteration 18 includes all 18 sectors on Bali. This also means that the graph in Figure 6 will be regenerated for each iteration, and will be based on an increasing sample size. The total building footprint areas calculated for Bali in each iteration is plotted in Figure 9. The same plot for an area around Amersfoort (the Netherlands) is displayed in Figure 10. Figure 9 shows that the calculated total building footprint area on Bali quickly converges to a value of approximately 157 km^2. In case of Amersfoort, the calculated total building footprint area also converges practically instantly, in this case to approximately 32 km^2. This confirms that the RAC methodology is convergent.

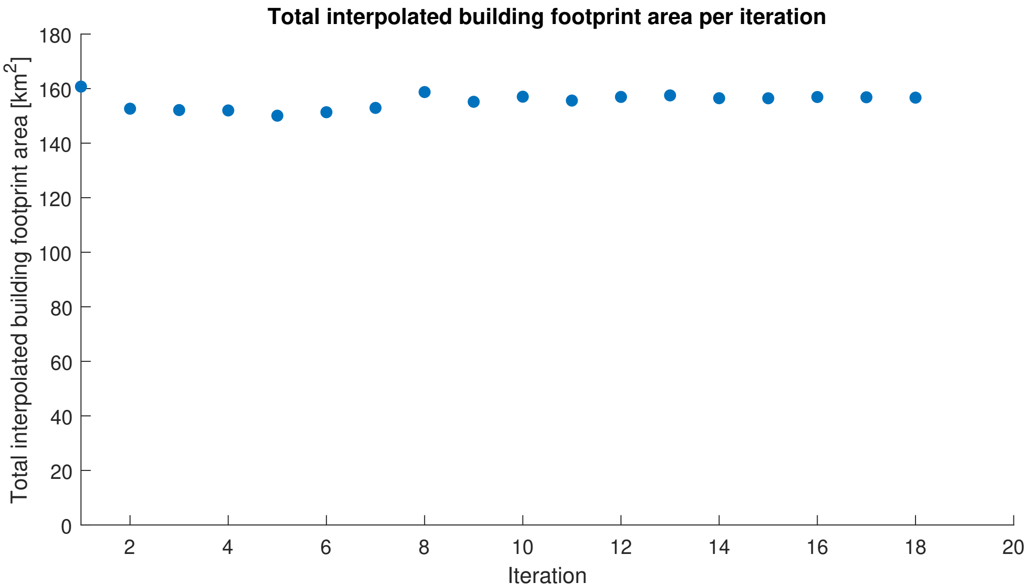

Figure 9: Plot of the total building footprint area on Bali resulting from each iteration.

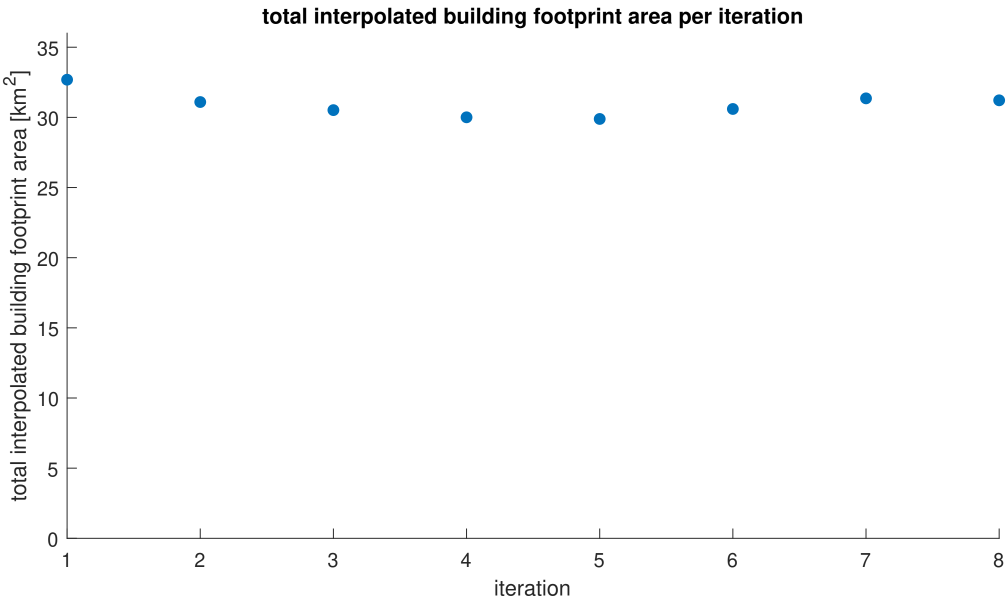

Figure 10: Plot of the total building footprint area in Amersfoort and surroundings resulting from each iteration.

4.2 Validation on sectors with complete building footprint data

In the second validation step, the RAC methodology is applied to a number of validation sectors in Western Europe and North America. These sectors were chosen because the OSM data in these regions is close to 100% complete according to OSM [37]. The methodology is applied to these sectors, and the resulting calculated building footprint area is compared to the actual building footprint area in that sector. Only the first filtering step — the removal of grid squares with nonzero built-up area density but containing no buildings — as described in Section 3.2 is applied here. The reason is that the second filter — the removal of underfull grid squares — is explicitly developed to compensate for missing OSM data. Since there is no OSM data missing in the validation sectors, the second filter is not required.

Table 3 summarizes the results of this validation, and the available parameters for Bali are included for reference. The calculated building area is the total building footprint area in the evaluated area as calculated with the RAC methodology. The overshoot factor is the calculated building area divided by the real building area, or the degree to which the calculated building footprint area exceeds the actual building footprint area. It should be noted that the overshoot factor is larger than 1 for all evaluated areas, implying that the calculated building area always exceeds the real building area. The overshoot ranges from 4.5% for Barcelona, Spain to 45.7% for Poitiers, France.

The spread and magnitude of the overshoot factors are significant. In order to clarify the causes behind this significant overshoot, the overshoot factor has been correlated to three other factors: the fullness factor, the maximum building area and the weighted average built-up area density. The fullness factor represents the share of grid squares with nonzero built-up area density that also have a nonzero building footprint area contained in them. The remaining grid squares with nonzero built-up area density have no buildings in them. Examples of built-up areas with no actual buildings can be, amongst others, roads, railways, rail yards, factory compounds, parks and parking lots. It can be expected that the overshoot factor is higher for areas with a lower fullness factor. The reason for this is that in the RAC methodology grid squares with nonzero built-up area density but zero building footprint area are assumed to contain incomplete OSM data, and are filtered out. However, the removal of grid squares with nonzero built-up area density that correctly do not contain buildings causes the average building footprint area associated with each percentage point of built-up area density to shift up. Consequently, the calculated building footprint area will exceed the actual building footprint area. The expected negative relation between the fullness and the overshoot factor appears to exist, as can be seen in Figure 11.

Location	Total area [km^2]	Real building footprint area [km^2]	Calculated building footprint area [km^2]	Overshoot factor	Fullness factor	Maximum building area [m^2]	Weighted average Built-up area density [%]
Barcelona SP	104	20	20.9	1.045	0.67	3300	62.5
Leiden NL	134	12.6	13.2	1.048	0.81	2600	40.0
Mannheim DE	1414	44	50	1.136	0.6	1900	15.6
Amersfoort NL	741	27.7	31.2	1.126	0.72	1700	17.7
Ottawa CAN	3786	58.1	70.6	1.215	0.54	1700	9.4
Alès FR	2763	15.5	20.6	1.329	0.55	1700	3.2
Kaltenkirchen DE	688	11.15	13.6	1.220	0.62	1500	8.9
Utrecht NL	2886	128.1	140.1	1.094	0.76	2100	20.1
Riom FR	647	9.6	12.7	1.323	0.51	1500	11.3
Copenhagen DN	303	21.9	24.4	1.114	0.7	1400	37.4
Poitiers FR	14869	95	138.4	1.457	0.47	1400	4.5
Bali IND	5170	-	156.7	-	-	2700	12.5

Table 3: Validation summary of the RAC methodology with available data for Bali included.

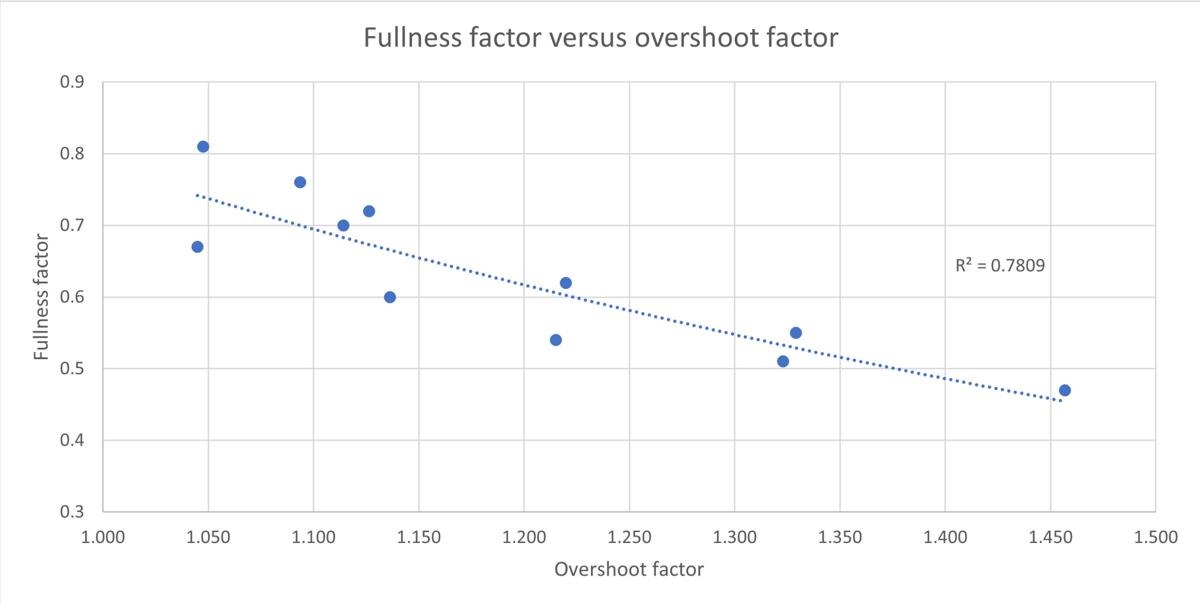

Figure 11: Correlation between fullness factor and overshoot factor in validation sectors.

While correlating the fullness factor with the overshoot factor is useful in explaining the nature of observed overshoots in validation sectors, it is not useful for estimating the overshoot for Bali. The reason behind this is that the fullness factor for Bali is unknown due to incomplete OSM data. In order to estimate the overshoot factor for Bali, it is preferable to correlate information that is contained in the data on Bali with overshoot factors observed in the validation sectors. One such information point is the maximum building area. The maximum building area is the average building footprint area associated with grid squares with 100% built-up area density. In the case of Bali this is approximately 2500 m^2 (Figure 6).

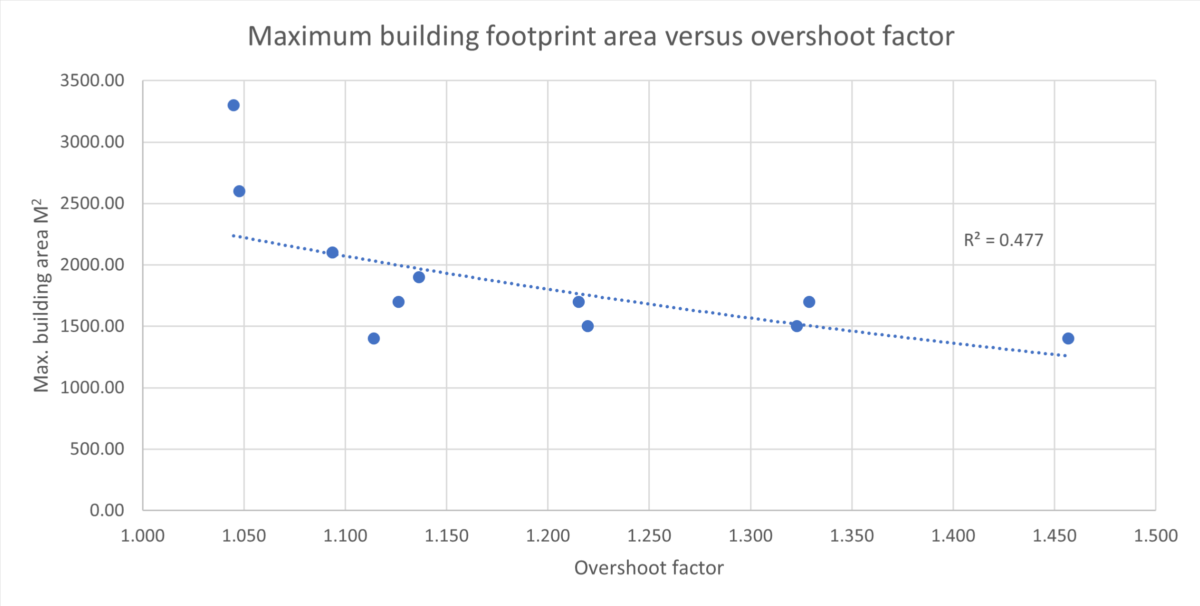

Figure 12: Correlation between maximum building footprint area and overshoot factor in validation areas.

A correlation between the maximum building area and the overshoot factor as observed in Figure 12 appears to exist, but the correlation is not as strong as the correlation between fullness and overshoot in Figure 11. Especially for areas with lower maximum building areas it is not possible to estimate the likely overshoot. For example, Copenhagen and Poitiers both have a maximum building footprint area of 1400 m^2, but Copenhagen has an overshoot factor of 11.4%, while Poitiers has a much higher overshoot of 45.7%. Another statistic that can be tested for correlation with the overshoot factor is the average built-up area density. This statistic is only related to the built-up area dataset, and is thus not affected by incomplete OSM data. The average built-up area density is the average of the built-up area density of all grid squares in an assessed sector.

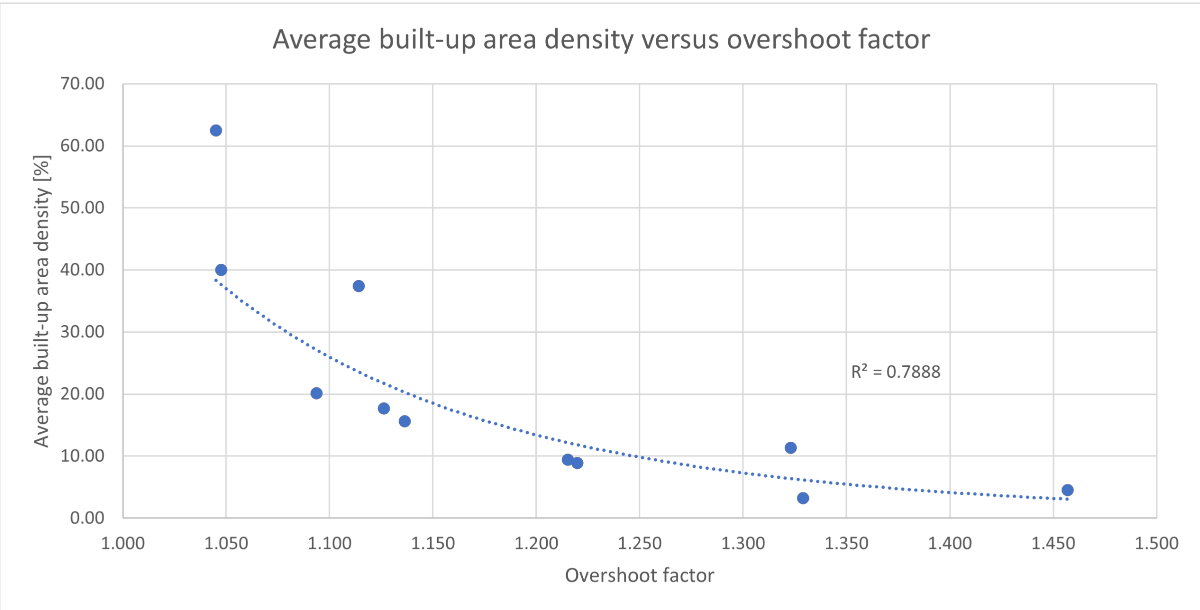

Figure 13: Correlation between average built-up area density and overshoot factor in validation areas.

This correlation is depicted in Figure 13, and it appears to be significant. As the overall average built-up area density of a region assessed with the RAC methodology decreases, the overshoot of the resulting total building footprint area increases. This correlation also raises the question whether a correlation exists between the aforementioned fullness factor and the average built-up area density. Figure 14 shows that this correlation appears to exist. The significant outlier at 62.5% built-up area density corresponds to the Barcelona validation sector. This sector is the smallest of all validation sectors and has a very high building density. This makes its results for the Barcelona validation sector less predictable and less representative as all other sectors have a significantly lower building density and larger area. If Barcelona is excluded, the R^2 in Figure 14 increases to 0.6742. Because a generally strong correlation exists between the overshoot and the average built-up area density of a sector, Figure 13 can be used to estimate the overshoot factor for any area to which the RAC methodology is applied.

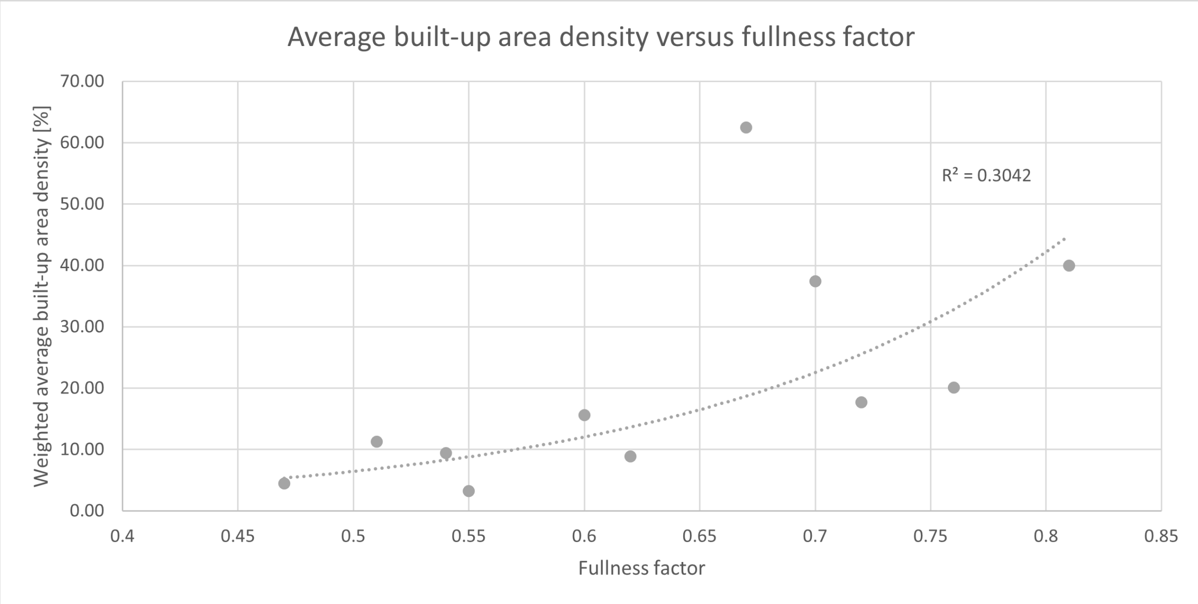

Figure 14: Correlation between weighted average built-up area density and fullness factor in validation areas.

4.3 Variance

The theory regarding the connection between high variance and inaccurate results conceptualized in Section 3.3 is tested on two validation sectors, one with a high deviation from the trendlines in Figures 13 and 14, and one with a low deviation. Barcelona (Figure 15a) has a high apparent deviation, peaking at $3.5 * 10^6 m^2$, while Leiden (Figure 15b) is very close to both trendlines. This would appear to support the hypothesis. However, Barcelona is also a considerably smaller validation sector than the others. Copenhagen (Figure 15c) also has a considerable deviation from both trendlines but its variance is much lower, lower even than Leiden. This disproves the theory regarding the connection between high variance and inaccurate results. There is also no apparent connection between variance and overshoot. If two large validation sectors — one with a large overshoot (Poitiers, Figure 15d) and one with a low overshoot (Utrecht, Figure 15e) — are compared, it can be observed that their variances are very similar. Two final observations are that the variance appears to truncate as the validation sector increases in area, and that the variance associated with grid squares with 100% built-up area density are considerably lower than preceding percentage points. To conclude, the variance of the underlying datasets does not appear to be a measure of the accuracy of the calculated total building footprint area.

The fact that there is no inherent connection found between high variance and inaccurate results can be explained by means of the shape of probability density functions. While the overall variance plots of Utrecht, Figure 15e and Copenhagen, Figure 15c differ considerably — Copenhagen has a lower variance than Utrecht — there is only a minor difference in overshoot, 9.4% versus 11.4%. However, when the probability density functions of the building footprint area for grid squares with 100% built-up area density in Utrecht and in Copenhagen are compared, this minor difference is explained. Figure 16 shows the probability density function for Utrecht, and Figure 17 shows the probability density function for Copenhagen. The spread of building footprint areas in Utrecht — the variance — is considerably higher than in Copenhagen. However, both probability density functions are still more or less symmetrical. As long as the distribution of building footprint areas above and below the median is symmetrical, the mean will not be skewed up or down. Consequentially, the resulting total building footprint area of the entire sector will not be skewed up or down. This topic will be continued in Section 4.4.

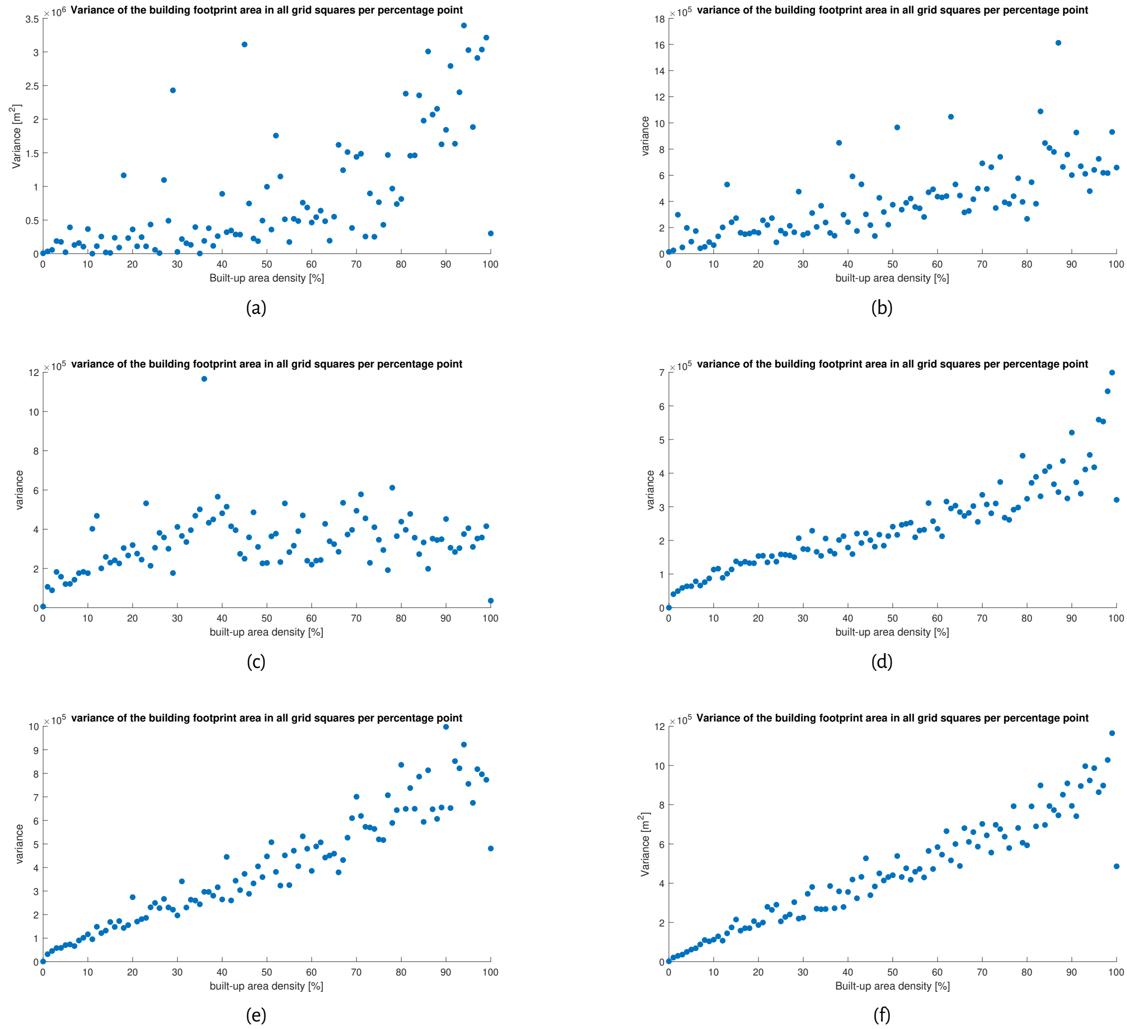

Figure 15: Variance in m^2 of the validation regions around Barcelona (a), Leiden (b), Copenhagen (c), Poitiers (d), Utrecht (e), and the variance of Bali (f).

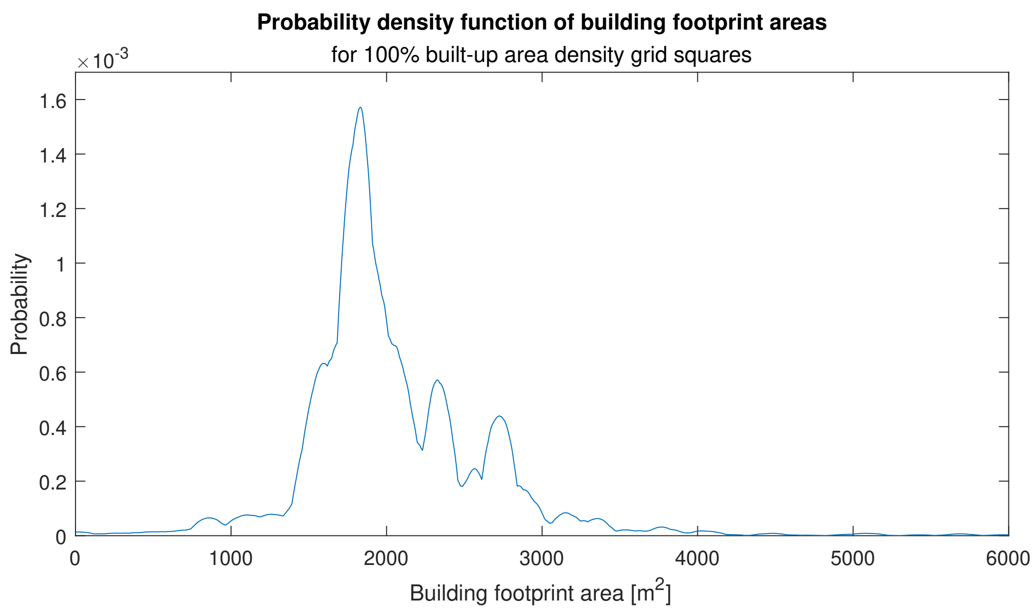

Figure 16: Probability density function of the building footprint area for grid squares with 100% built-up area density in Utrecht

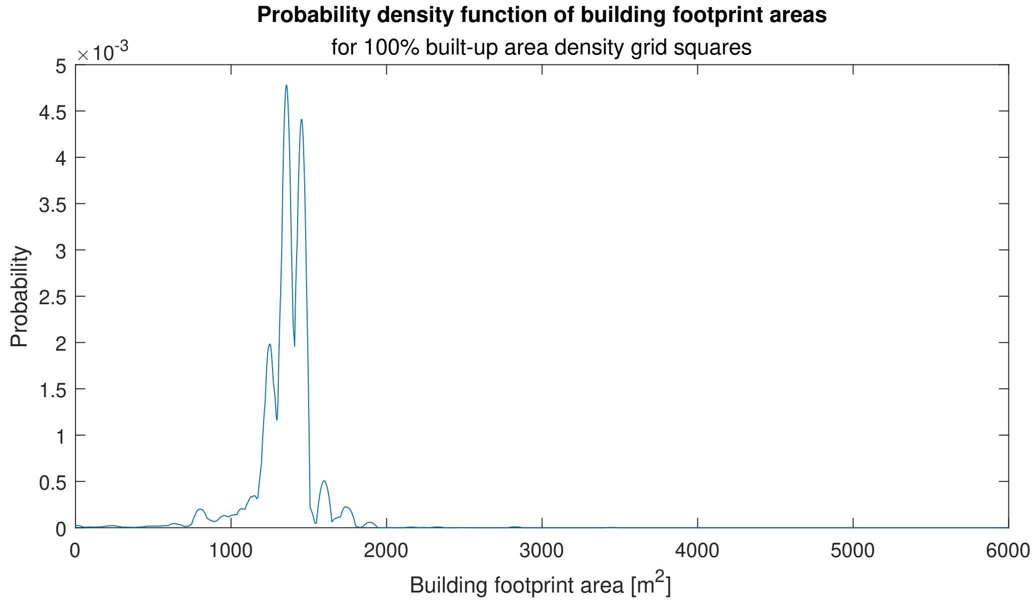

Figure 17: Probability density function of the building footprint area for grid squares with 100% built-up area density in Copenhagen

4.4 Validation on sectors with building footprint data made artificially incomplete

Previous validations were conducted on sectors with intact and complete OSM data. In Section 4.1 on convergence it has been shown that only a relatively minor sample of the total available data is required to achieve a reliable result. This approach to validating with missing data works by omitting large parts of both OSM data and built-up area data. However, this manifestation of incomplete OSM is likely not an accurate representation of how missing data is actually distributed in the case of Bali, or any other area with incomplete OSM data. Figure 4 shows the real life manifestation of missing data, which is on much smaller scale. Notably, in reality there will be grid squares with nonzero built-up area density and also nonzero building footprint area, even though OSM data is incomplete. In other words, there will be grid squares with almost entirely missing OSM data which are not filtered out by the first filtering step, as there are still a few buildings present. As a result, there will be grid squares with less building footprint than there should be (underfull grid squares), but they will not be omitted because the associated built-up area density is still nonzero. The expected result of this will be that the average building footprint area associated with each percentage point of built-up area density will decrease. In turn, this will cause the calculated total building footprint area to be lower than the actual building footprint area. This can be described as an 'undershoot' effect. This undershoot effect will counteract the overshoot effect found to be innate in the RAC methodology in Section 4.2.

This smaller scale manifestation of missing OSM data should be visible in the variance of the total dataset, as discussed in Section 4.3. The reason is that if there are a number of grid squares with incomplete but not entirely absent OSM data, the building footprint area contained in them should be much lower than the average building footprint area associated with grid squares of that percentage point of built-up area density. This effect should be visible in a plot of the probability density function. Where the probability density function for a sector with complete OSM data should be more or less symmetrical — such as in Figure 16 — a sector with incomplete data should have a noticeable increase at the lower end of the building footprint area range. Figure 18 shows the probability density function of the building footprint area for grid squares with 100% built-up area density on Bali. The predicted increase at the lower end of the building footprint area range is marked in the red box.

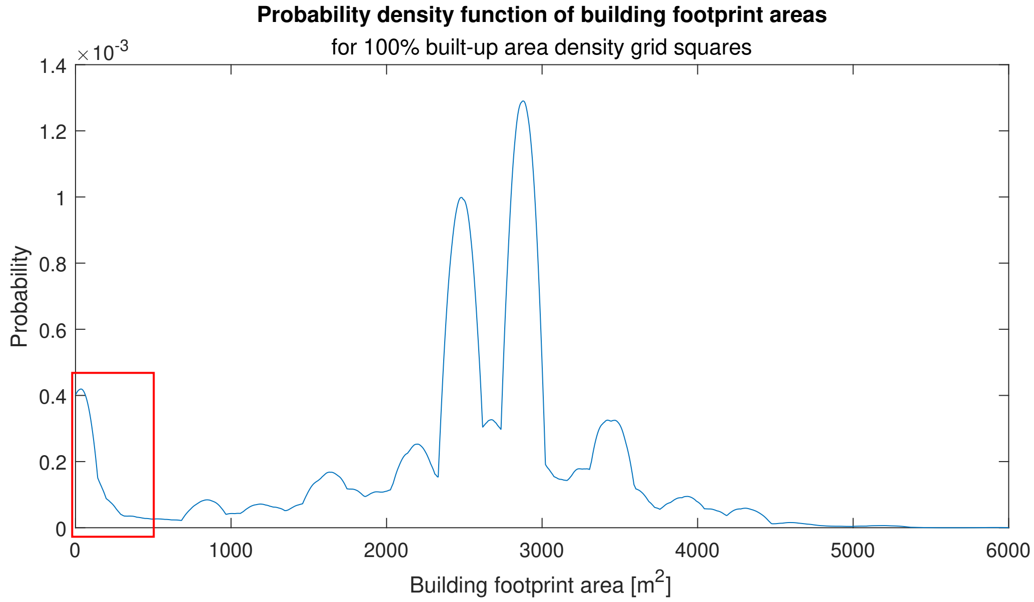

Figure 18: Probability density function of the building footprint area for grid squares with 100% built-up area density on Bali.

In order to estimate the effect on the total building footprint area of this phenomenon, and in order to assess whether it is possible to effectively filter out this incomplete data, the effect will be replicated on the province of Utrecht, which is one of the validation sectors introduced in Sector 4.2. In order to simulate the type of data incompleteness on Bali rectangular sections have been cut out of the building footprint map of Utrecht at random, which amounted to 24% of total building footprint area removed, both in urban and rural areas. It should be noted that this process was conducted manually, consequentially the actual randomness of the removed parts cannot be quantitatively verified. Figure 19 shows the resulting probability density function. The same increase in probability density at the left side of the graph is visible as in Figure 18. The total building footprint area that was calculated with the RAC methodology based on the incomplete Utrecht data was 129.2 km^2, which is equivalent to a 0.9% overshoot. Notably, this is actually closer to the actual building footprint area of 128.1 km^2 than the building footprint area calculated using the complete dataset, which was 140.1 km^2. This quantifies the aforementioned undershoot effect as approximately 10% opposite to the overshoot effect.

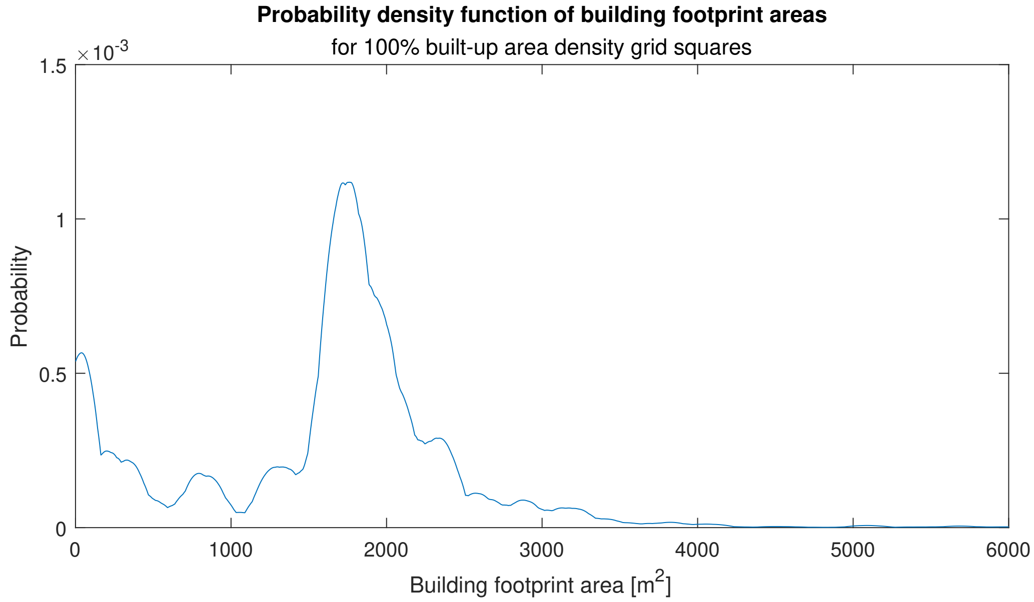

Figure 19: Probability density function of the building footprint area for grid squares with 100% built-up area density in Utrecht with 24% of building footprint area removed.

This undershoot effect can be corrected by filtering the bottom 20% of the building footprint area data. This bottom

20% represents most of the underfull grid squares. This will remove the grid squares with incomplete but nonzero OSM data that cause the increase on the left side of the probability density function in Figure 19. After adding this filter, the calculated total building footprint area is 142.3 km^2. The resulting probability density function is shown in Figure 20.

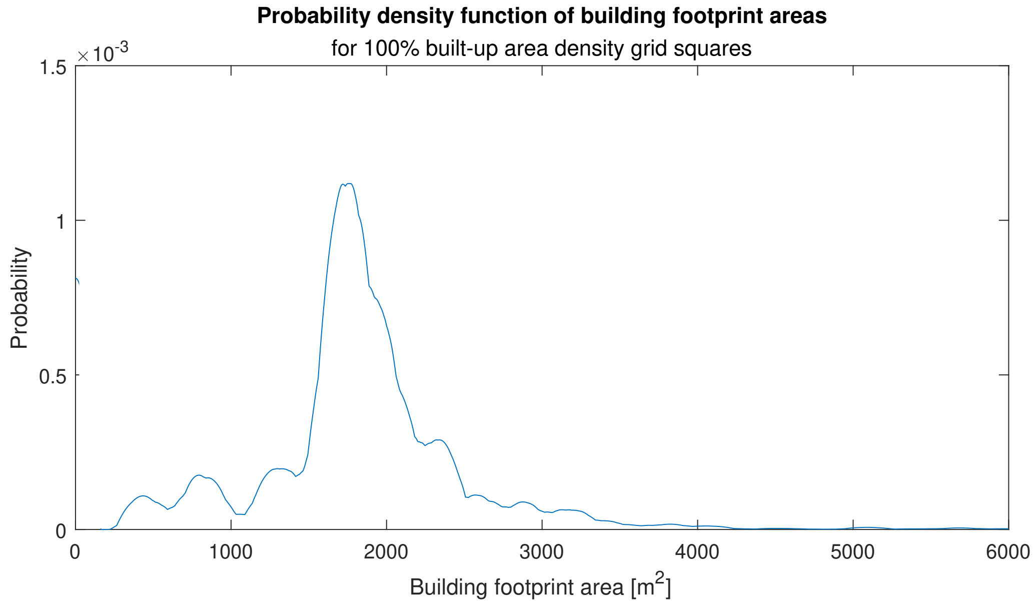

Figure 20: Probability density function of the building footprint area for grid squares with 100% built-up area density in Utrecht with 24% of building footprint area removed. The bottom 25% of building footprint areas is filtered out.

In conclusion, this section has shown that the type of data incompleteness on Bali causes an undershoot effect due to grid squares that have OSM data that is incomplete but not totally absent. This undershoot effect has a magnitude of approximately 10%, and it opposes the overshoot effect. This undershoot effect can be corrected by filtering out the underfull grid squares by adding a filter that removes the grid squares with the lowest 20% building footprint area for each percentage point of built-up area density.

4.5 Validation conclusion

In order to validate the reliability and accuracy of the RAC methodology, the methodology was applied to a number of validation sectors with OSM data that is known to be complete. A number of conclusions can be drawn from the validation process of the RAC methodology. First of all, the RAC methodology converges rapidly as sample sizes increase. As a result, relatively small samples are required to achieve consistent results. Second, an inherent overshoot effect was found. This effect is a direct result of the filtering of grid squares with nonzero built-up area density and zero building footprint area on the presumption that the building footprint data is incomplete. A share of this data is rightfully ascribed no buildings, as it represents built-up areas without buildings such as roads, railroads, railyards, parks, some industrial areas, etc. The degree of overshoot ranges from 4.5% to 45.7% in sampled validation sectors.

This range of potential overshoot factor is significant, which could be considered problematic. However, there is a strong correlation between the overshoot factor and the weighted average built-up area density of the sample area, and between the overshoot factor and the fullness factor of the sample area. The fullness factor can only be calculated for areas with complete OSM data, but the weighted average built-up area density can be calculated for any area. The correlation between the overshoot factor and the weighted average built-up area density can then be used to estimate the degree of overshoot of the total building footprint area that is calculated with the RAC methodology. Third, the variance of the building footprint area in all grid squares per percentage point was analyzed. The goal of this was to assess whether a higher variance is connected to less reliable results, but this connection was not found. Fourth, the RAC methodology was applied to a sector with parts of the building footprint data cut out. It was shown that incomplete building footprint data leads to an undershoot effect of approximately 10% that opposes the overshoot effect found in Section 4.2. This undershoot effect can be corrected by means of an additional filter that removes most of the grid squares with incomplete but nonzero building footprint data (underfull grid squares).

5 Results

In this chapter, the results of this thesis research are discussed. First, the RAC methodology to calculate rooftop area is applied to Bali in Section 5.1. Second, the technical potential of RTSPV on Bali as a whole and for individual rooftops is calculated and discussed in Section 5.2. Third, the economic potential of RTSPV on Bali is assessed based LCOE and by modeling an example household, and a sensitivity analysis is performed in Section 5.3. Last, the results found in this research are compared to other publications on RTSPV potentials in Indonesia in Section 5.4.

5.1 Total rooftop area estimation

The validation process in Chapter 4 has shown that the building footprint area calculated for a target area with the RAC methodology overshoots the actual building footprint area in that target area. The magnitude of this overshoot can be estimated using the weighted average built-up area density of the target area. In this section, the results of the application of the RAC methodology on Bali will be discussed. The average building footprint area associated with each percentage point of built-up area density on Bali is depicted in Figure 21.

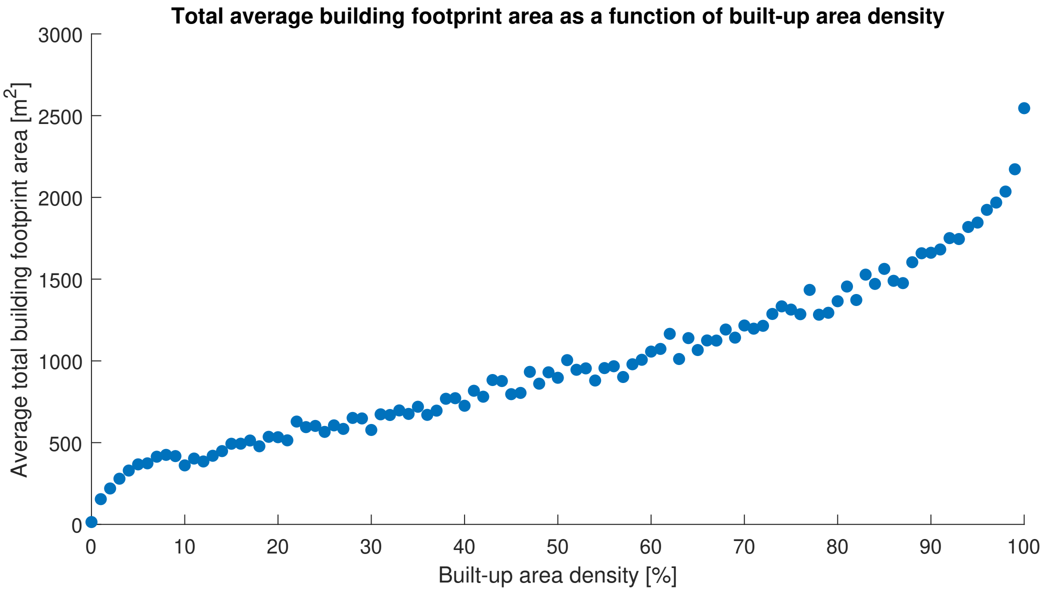

Figure 21: Average building footprint area associated with each percentage point of built-up area density on Bali.

The variance of the building footprint area in all grid squares per percentage point of built-up area density on Bali is depicted in Figure 15f. The shape of the scatter plot is visually similar to that of Poitiers (Figure 15d) and Utrecht (Figure 15e). The maximum variance peaks at approximately $12 * 10^5 m^2$, which is slightly higher than Utrecht. However, this amount of variance has not been found to be connected to inaccurate results in Section 4.3. Furthermore, the accuracy of the built-up area data of Bali is comparable to the rest of the world [34], meaning that it is unlikely that the accuracy of the built-up area data causes the methodology to behave differently than in Western Europe, where most validation was performed. It is assumed that the same process which proved to be effective for Utrecht in Section 4.4 also applies to Bali. The reason is is that the distribution of missing building footprint data on Bali is similarly distributed between urban and rural areas as for Utrecht with manually removed building footprint data. The calculated building footprint area for Bali is 156.7 km^2 using the methodology described in Section 3.2, and the weighted average built-up area density is 12.5%.

Using the trendline in Figure 13, the overshoot can be estimated to be 20%. After correcting for the overshoot factor, a likely estimate for the total building footprint area on Bali is approximately 130 km^2. Total horizontal rooftop area is assumed to be identical to total building footprint area. As discussed in Section 3.1, satellite images show that, where OSM data is available, actual building footprint areas likely exceed the building footprint areas mapped by OSM by 25%. As a result, the estimate of 130 km^2 is a conservative estimate of the actual building footprint area. The effect of the mean error in the Copernicus built-up area density dataset of 1.5% depends on the density of the grid square where the error occurs. As the function in Figure 21 is not linear, the effect of a grid square with a density of 99% being misrepresented as having a 100% built-up area is greater than one with a density of 30% being misrepresented as having a density of 31%. Any errors in the built-up area density dataset will manifest in the calculated building footprint area. As the accuracy of the Copernicus data of Bali is similar to that in the regions where the validation was performed, and the overshoot and therefore the building footprint area can be adequately estimated by means of Figure 14, the specific accuracy of the Copernicus data is of no concern. If there would be gross inaccuracies in the Copernicus data, they would have been discovered as part of the validation in Section 4.

5.2 Technical potential estimation

In this section, the technical potential of RTSPV on Bali is estimated. First, the effects of rooftop geometry are explored in Section 5.2.1. A shading model is constructed in Section 5.2.2 and the RTSPV yield reduction as a consequence of increasing degrees of shading is calculated. Using the insights from estimating the effects of rooftop geometry and shading, the total technical potential for RTSPV on Bali is estimated in Section 5.2.3. Additionally, a model is proposed in Section 5.2.4 with which the technical potential of an individual rooftop can be estimated. Last, a sensitivity analysis is conducted on the technical potential in Section 5.2.5.

5.2.1 Rooftop geometry effects

The Solargis solar power potential dataset used to estimate the total technical potential of RTSPV on Bali is based on a horizontal reference plane. However, most rooftops on Bali are in fact not flat. In order to obtain an accurate estimate of the technical potential of RTSPV on Bali, the effects of realistic rooftop geometries need to be calculated. Initially no considerations will be made regarding shading, as this will be considered in Section 5.2.2. In this section, the Meteonorm hourly solar irradiance dataset for Denpasar will be used. The use of this data allows for the modeling of the effects of rooftop geometry on irradiance and overall yield. This is not possible with the Solargis data. In Figure 22 the average annual irradiance on Denpasar rooftops is plotted as a function of rooftop tilt.

The annual irradiance at a specific degree of tilt is the average of the irradiance on a rooftop with that tilt calculated at all 360 degrees of rooftop azimuth. The reason behind calculating the average irradiance at all 360 degrees of rotation is the large number of rooftops on Bali. This allows for the assumption to be made that the azimuth of all rooftops on Bali is uniformly distributed over all 360 degrees of rotation. Figure 22 shows that average annual irradiance is highest for horizontal roofs at 2028 kWh/m^2/year. If rooftops are tilted at $30°$, the average annual irradiance drops to 1832 kWh/m^2/year. The right y-axis represents the normalized irradiance values as a percentage of the maximum irradiance. While the exact values for annual irradiance are specific to Denpasar weather, the normalized values are only a result of the changing orientation of the solar module relative to the sun. Since all of Bali is geographically close to Denpasar, the normalized irradiance, PV potential (Figure 23) and annual total yield (Figure 24) values can be applied to all of Bali.

In order to calculate the total annual electricity yield per kWp (equal to the PV potential) in Denpasar, an RTSPV module needs to be selected. The module chosen for this research is the SunPower X22-370. It has a nominal power of 370W, an area of 1.63 m^2 and an efficiency of 22.7% under standard test conditions [47]. The module efficiency decreases by 7% to 21.1% as a consequence of temperature effects. Additionally, Balance of Systems efficiency (BoS, efficiency of all other parts of the RTSPV installation such as the inverter and cabling [39]) of 91% is assumed. By subjecting this solar module to the irradiance function depicted in Figure 22, and applying Equation 3 the PV potential as a function of tilt in Denpasar can be calculated, which is depicted in 23. It should be noted that the maximum PV potential calculated by this method — 1720 kWh/kWp/year — is higher than the highest PV potential in Denpasar according to Solargis data of 1666 kWh/kWp/year (See Figure 3). This difference can be attributed to differences in measuring methods and measuring time periods.

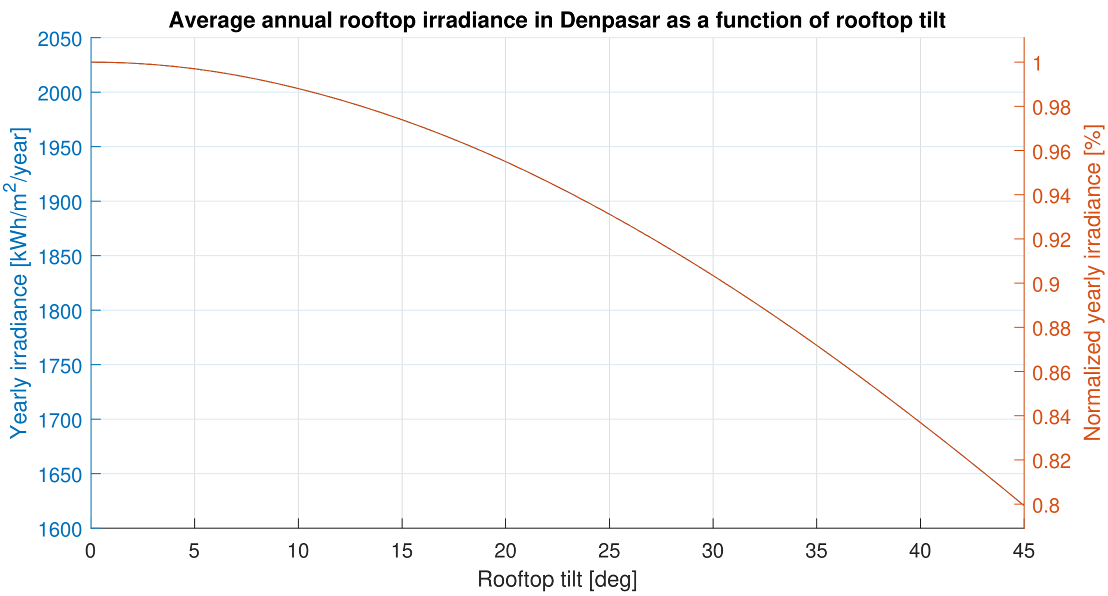

Figure 22: Average annual rooftop irradiance in Denpasar as a function of rooftop tilt.

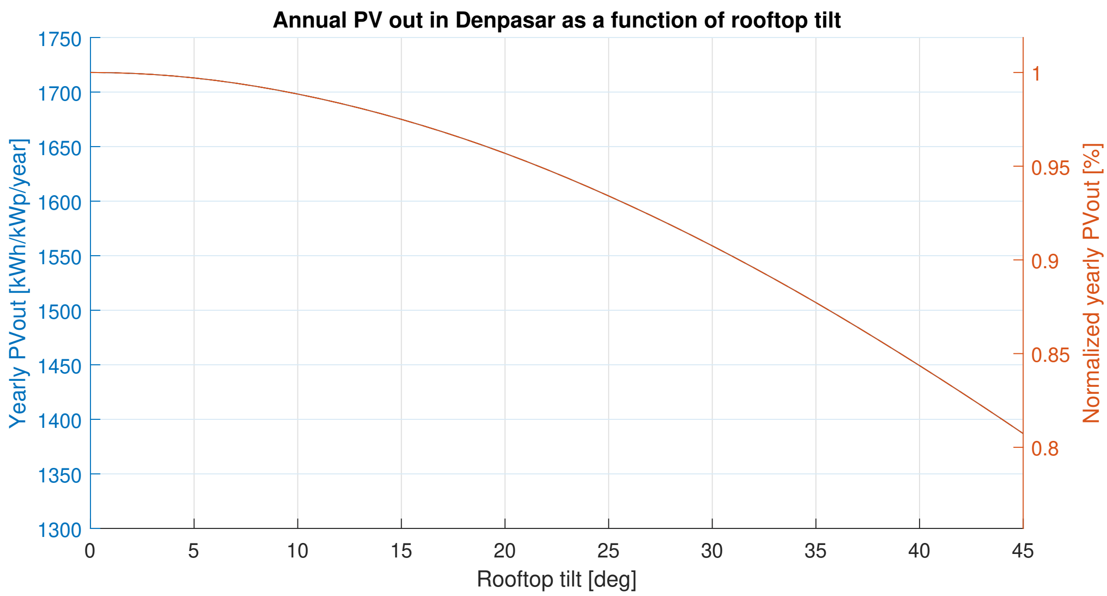

Figure 23: Annual PV potential in kWh/kWp/year as a function of rooftop tilt in Denpasar.

The normalized total annual yield in kWh of all of Denpasar, again assuming a homogeneous distribution of rooftop azimuths between $0°$ and $359°$, is plotted in Figure 24. Notably, while PV potential decreases for increasing rooftop tilt, the total yield increases as rooftop tilt increases. The PV potential decreases with approximately 9% for a tilt of $30°$, but overall yield increases by approximately 5% compared to horizontal rooftops. The reason is that the actual surface area of the roof increases as rooftop tilt increases. This allows for a larger surface area to be covered with solar modules for the same building footprint area. This increasing surface area compensates for the reducing PV potential as rooftop tilt increases. In conclusion, increasing rooftop tilt has a positive effect on overall RTSPV yield. As a result, employing the Solargis dataset — which assumes horizontal rooftops — actually results in a slightly conservative estimate of the total technical potential of RTSPV on Bali.

5.2.2 Shading effects

In the last section, no consideration was made for shading. In Section 3.4.3, a simplified model was proposed to assess the effects of shading resulting from a simplified obstruction. This obstruction blocks direct and indirect irradiance

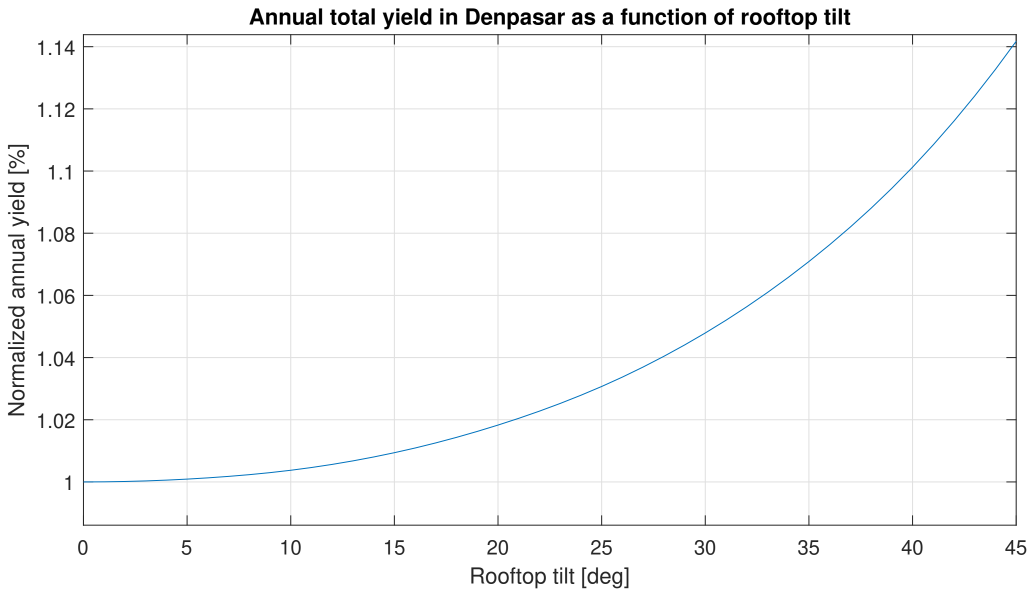

Figure 24: Normalized annual yield relative to the yield for horizontal rooftops in Wh/year as a function of rooftop tilt in Bali.

below a certain attitude a_{block}. In Table 4, the effects of a shading attitude a_{block} between $0°$ and $60°$ on the annual PV potential on Bali are summarized. The reduction percentages also apply to the annual yield [TWh/year]. To add context, a comparison is made to shading in Delft, the Netherlands, using Delft Meteonorm data for the same time period. Delft is situated at $52°$ latitude, and is therefore much further from the equator than Bali. As a result the sun rises to a lower attitude than Bali, and the reduction of PV potential [kWh/kWp/h] as a consequence of a specific blocking angle should therefore be higher than on Bali. This is confirmed in Table 4.

Effects of shading on a horizontally mounted RTSPV module on Bali compared to Delft				
Blocking angle [deg]	Annual PV out Bali [kWh/kWp/year]	Annual PV out reduction Bali [%]	Annual PV out Delft [kWh/kWp/year]	Annual PV out reduction Delft [%]
0	1720	0	910	0
10	1594	7.3	815	10.4
20	1448	15.8	685	24.7
30	1252	27.1	535	41.1
40	1011	41.2	374	58.9
50	784	54.4	215	76.4
60	456	73.5	80	91.2

Table 4: Reduction in annual PV potential as a result of shading on Bali compared to Delft, the Netherlands.

5.2.3 Estimation of total technical potential of RTSPV on Bali

In the previous sections, the effects of rooftop geometry and shading were assessed. It was concluded that tilted rooftops do not result in a decrease in the technical potential of RTSPV in Section 5.2.1. Additionally, a shading model was constructed that estimates the effects of shading. If the methodology described in Section 3.4.1 is applied to all of Bali assuming horizontal rooftops, the resulting installable capacity is 28.4 GWp with a utilization factor of 100%. In other words, assuming the entire 130km^2 of rooftop area is covered in solar modules. The resulting technical potential is 43.1 TWh/year. The average PV potential of all grid squares, weighted by the rooftop area in each square, is 1516 kWh/kWp/year.

The rooftop utilization factor being set at 100% is not realistic, as it is unlikely that it is possible to fully cover all rooftops on Bali with solar modules. However, it is also not possible to calculate the actual utilization factor for all buildings on Bali. As a result, the utilization factor has to be estimated. One possible method to estimate the rooftop utilization factor is to construct an average building that is representative of all those on Bali. This has been done by taking a square building with as the footprint area the average building footprint area on Bali, which is derived from the OSM building footprint data. This average building footprint area has been found to be 120 m^2. Since most roofs on Bali are hip roofs, the square roof has been divided into four triangles. These triangles were then filled with the maximum amount of SunPower X22-370 modules that fit within the borders of each triangle. This resulted in 48 modules being installed on the rooftop of this average building, leading to a rooftop utilization factor of 63%. Since the installable capacity and the technical potential scale linearly with the utilization factor, the installable capacity becomes 17.9 GWp and the resulting technical potential 27.2 TWh, again assuming horizontal rooftops.

While a shading model was constructed in Section 5.2.2, it is difficult to estimate the average shading that all rooftops on Bali are subjected to. However, when it is assumed that all rooftops on Bali are subjected to a blocking angle of 20° due to neighbouring buildings, the resulting reduction in yield due to shading is 15.8%. Applying this reduction to the annual yield with a utilization factor of 63%, the technical potential decreases to 22.9 TWh/year. When rooftops are not assumed to be horizontal, but hip roofs with a segment tilt of 30°, the technical potential increases to 23.4 TWh/year for a capacity of 21.4 GWp.

The total annual electricity demand on Bali in 2020 was 4.95 TWh, down considerably from 5.71 TWh in 2019 [48]. Since this decrease was potentially caused by the CoVID-19 pandemic, the 2019 figure is therefore perhaps more suitable to use as a comparison. When considering the least favourable technical potential — resulting from horizontal roofs with a utilization factor of 63% and a 15.8% yield reduction due to shading — on Bali of 22.9 TWh/year, the technical potential is a factor 4 higher than current electricity consumption.

5.2.4 Individual rooftops

Previously, all calculations regarding annual yield were made by averaging irradiance on a tilted surface over all 360 degrees of azimuth. However, in order to assess RTSPV installations on individual buildings with tilted roofs, the effect on total irradiance of specific degrees of azimuth should be known. This effect is shown for a rooftop tilted at 30° in Figure 25. Notably, the reflected irradiance is negligible. As expected from the geographical location of Bali, the least optimal orientation for a tilted solar module is due south. The dependence of irradiance on azimuth translates directly to annual PV potential, as can be seen in Figure 26. The PV potential is normalized relative to the average irradiance on the right y-axis. The average PV potential is approximately 1560 kWh/kWp/year, equal to the PV potential for a 30° tilt in Figure 23. For a horizontal rooftop and solar module, the graphs in Figures 25 and 26 would both be flat, as irradiance and PV potential are not influenced by rooftop azimuth. By utilizing Figure 26, the annual PV potential can be calculated for any hypothetical unshaded rooftop with a 30° tilt on Bali. If the rooftop is in the vicinity of other buildings or obstructions, Table 4 can be used to estimate the effect of shading on annual yield. In case of a tilted rooftop experiencing this type of shading, the modules mounted higher up on the roof will receive solar irradiation earlier than the modules mounted at the bottom of the roof. This approach, however, assumes that the entire RTSPV installation will only start producing electricity once the lowest mounted solar module is fully irradiated. As a result, this approach produces a conservative estimate for the yield of an RTSPV installation when accounting for shading.

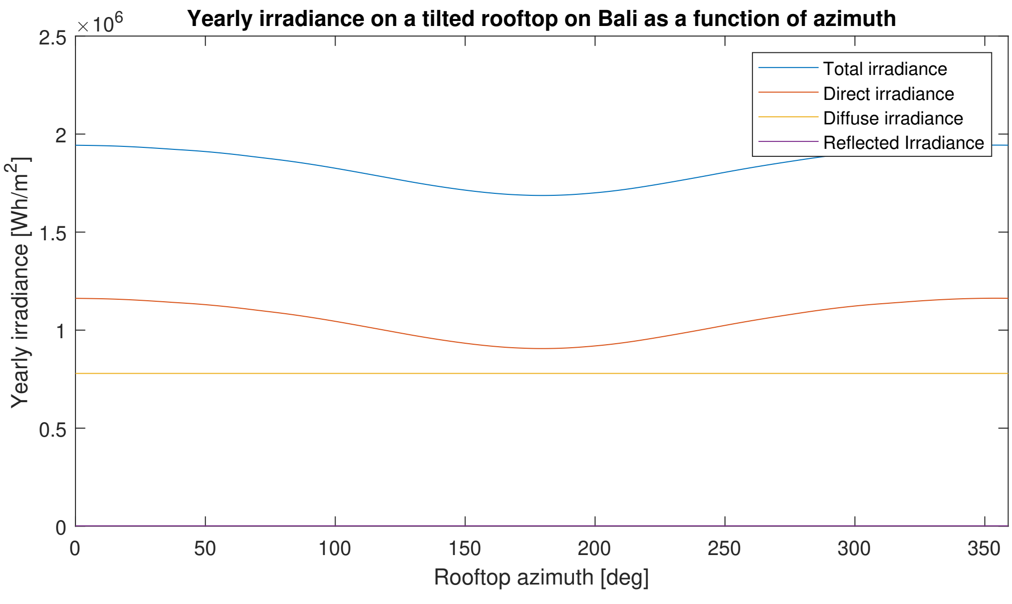

Figure 25: Effect of azimuth on irradiance components for a rooftop on Bali tilted at 30°.

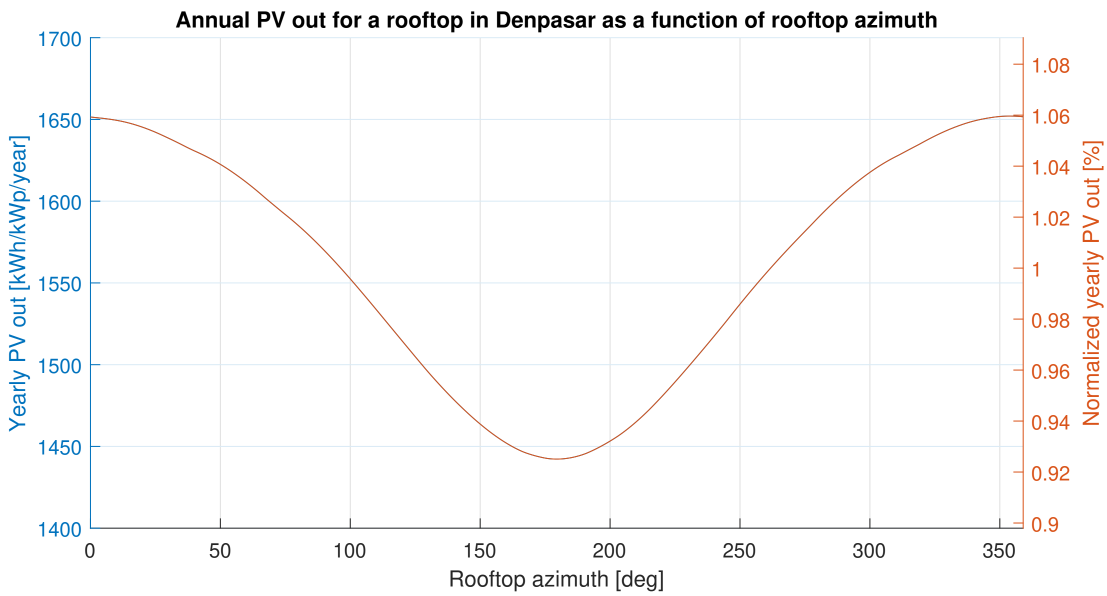

Figure 26: Effect of azimuth on PV potential for a rooftop in Denpasar tilted at $30°$.

5.2.5 Sensitivity analysis of technical potential

A sensitivity analysis is performed on the total annual yield on Bali. The base case technical potential is 222.9 TWh/year, which is based on a total rooftop area of 130 km^2, a utilization factor of 63%, a roof tilt of $30°$, a shading attitude of $20°$. The sensitivity of the total annual yield to these parameters is calculated by varying each parameter individually by -20% and +20%. The results can be seen in Figure 27. The results show that a variation of the PV potential, rooftop area and utilization factor translates to an identical variation of the technical potential. An increase of the roof tilt also induces an increase in the technical potential, while an increase in shading causes a reduction of the technical potential.

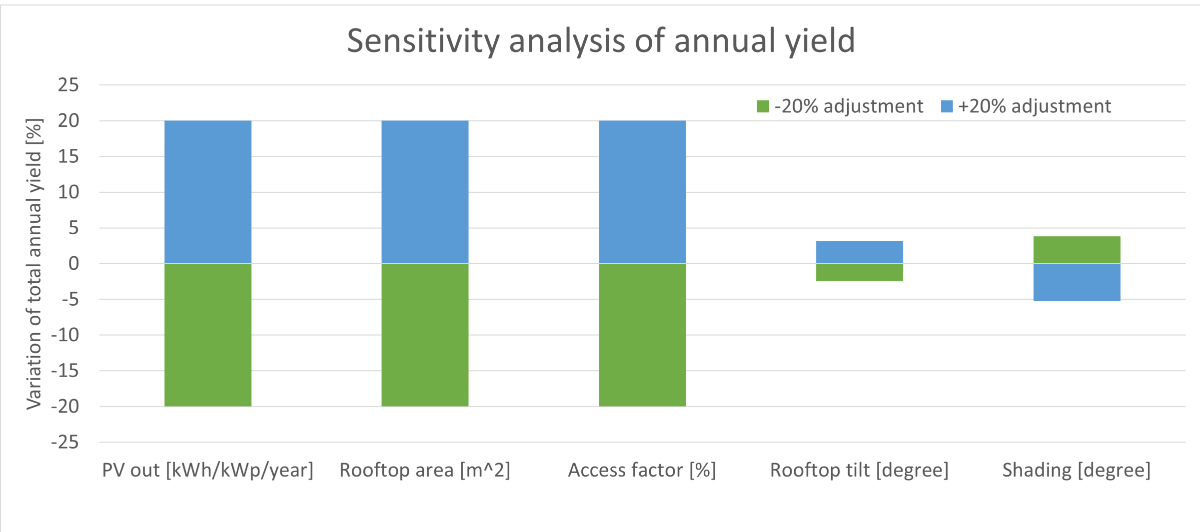

Figure 27: Sensitivity analysis of the technical potential of Bali.

5.2.6 Technical potential conclusion

The first step in calculating the technical potential was the approximation of the total rooftop area available on Bali. This was calculated to be 130 km^2. Secondly, the relationship between rooftop tilt and total yearly yield was established. It was found that as rooftop tilt increases, the total yield increases as well. The reason for this effect is that, as rooftop tilt increases, the surface area of the rooftop also increases. On the other hand, the total irradiance on rooftops decreases as tilt increases. However, because the rooftop areas increases more significantly than the irradiance decreases for an increasing rooftop tilt, total annual yield increases with rooftop tilt. An average utilization factor (fraction of a rooftop able to be covered with solar modules) for Bali was estimated to be 63%, based on an average rooftop area of 120 km^2. A shading model for Bali was also constructed, and the RTSPV annual yield reduction was estimated to be 15.8%. As a result of these parameters, the total technical potential of RTSPV on Bali is estimated to be 22.9 TWh/year. This technical potential exceeds the annual electricity demand of Bali by approximately a factor 4.

5.3 Economic potential

In this section the economic potential of RTSPV on Bali will be estimated. First, the average CAPEX and OPEX for RTSPV components are estimated in Section 5.3.1. With this information, the LCOE and total economic potential of RTSPV is estimated in Section 5.3.2. In Section 5.3.3 the economic performance of individual RTSPV installations is modeled. A sensitivity analysis of the LCOE and the IRR of RTSPV installations is performed in Section 5.3.4. Last, policy options to increase the economic potential of RTSPV are discussed in Section 5.3.5.

5.3.1 Estimating CAPEX and OPEX

The first step in assessing the economic potential of RTSPV on Bali is estimating the price of RTSPV installations. Personal communication between the author with Global Buildings Performance Network (GBPN), and information obtained from NUSA Solar [49], an Indonesian RTSPV installation company, indicate a current consumer price for residential RTSPV installations of 1200 USD/kWp, which applies to installations larger than 7kWp. This is comparable to the average costs in Thailand, Spain, and Australia [50]. Since RTSPV is currently a small market in Indonesia with less than 4000 RTSPV installations installed in the entire country [5, 6], the number of companies offering the installation of RTSPV installations is small, and consequently economies of scale are small as well. As the industry grows, prices can potentially decrease. An example is India, where residential RTSPV installations cost 658 USD/kWp on average [50].

Maintenance costs (OPEX) are difficult to estimate for non-utility scale RTSPV installations. Potentially, the only maintenance necessary for RTSPV installations is periodical cleaning [39], which can be done by the owner at negligible cost. Another estimate of OPEX, based on utility-scale solar installation OPEX, is 10-18 USD/kWp/year [50].

5.3.2 Levelized cost of electricity and total economic potential

The LCOE as defined in Section 3.5 is calculated as a function of CAPEX, OPEX, the discount rate and the annual yield. The annual yield is a function of PV potential. CAPEX, OPEX and the annual yield are additionally all linear functions of the total capacity of the RTSPV installation. Consequentially, the capacity cancels out, and the LCOE is independent of the capacity of the RTSPV installation. CAPEX, OPEX and the discount rate are assumed to be constant throughout Bali, the annual yield is therefore the only location and orientation dependent factor. As discussed in Section 3.5, three levels of grid parity will be assessed. The first level is when the LCOE of RTSPV is equal or lower than the consumer electricity price of 0.1 USD/kWh, the second level when it is equal or lower than the commercial electricity price of 0.075 USD/kWh, and the third level is when it is equal or lower than the BPP of 0.063 USD/kWh. Figure 28 shows the total economic potential for both values for the LCOE assuming horizontal rooftops. The total technical potential of 22.9 TWh/year can be achieved at a CAPEX of 600 USD/kWp, 750 USD/kWh, and 1000 USD/kWp for an LCOE of 0.063 USD/kWh, 0.075 USD/kWh, and 0.1 USD/kWh respectively assuming horizontal rooftops. The underlying reason for the achievement of grid parity at those CAPEX is that the PV potential in all of Bali is sufficient to generate electricity at or below the given LCOE. As CAPEX increases, the economic potential decreases gradually. The reason for this decrease is that the required PV potential increases as CAPEX increases for the same LCOE. As a consequence, some areas of Bali will have a PV potential that is too low to generate electricity at the given LCOE, hence the reduced economic potential. The effect of PV potential on the LCOE is depicted in Figure 29, where the LCOE is calculated as a function of PV potential and CAPEX.

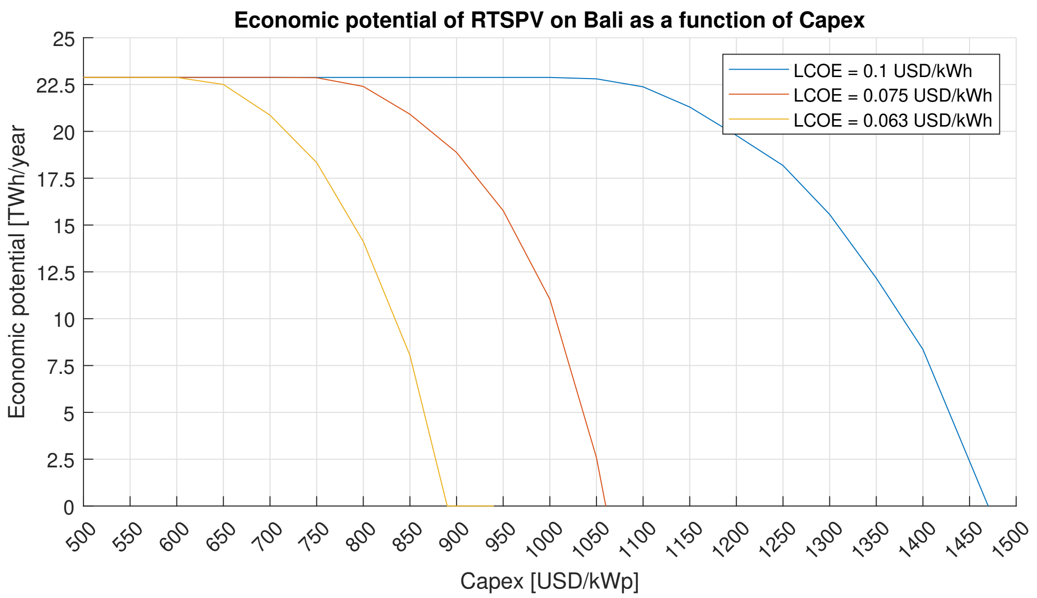

Figure 28: Economic potential of RTSPV [TWh/year] on Bali as a function of CAPEX [USD] for an LCOE of 0.063 USD/kWh, 0.075 USD/kWh and 0.1 USD/kWh, horizontal rooftops.

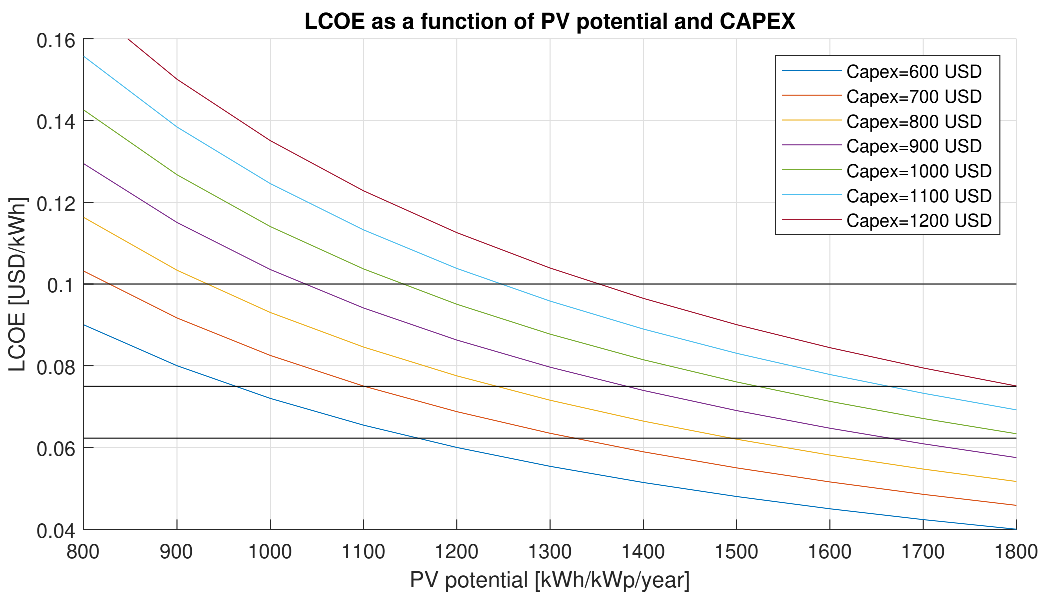

Figure 29: LCOE of RTSPV as a function of PV potential and CAPEX, markers on 0.063 USD/kWh, 0.075 USD/kWh and 0.1 USD/kWh.

As discussed in Section 5.2.3, the total technical potential increases to 23.4 TWh/year when rooftops are assumed to be hip roofs with segments tilted at $30°$. While the technical potential increases, the average irradiance received by tilted rooftops is lower, resulting in a lower yield per solar module. As a consequence, the LCOE of RTSPV will increase. Due to this, the economic potential for the same CAPEX will be lower than for horizontal roofs. In reality, however, it is likely that solar modules will initially be mounted on parts of the roof that receive the most solar irradiance, which means that for lower values of the economic potential, the CAPEX threshold of 900 USD/kWp for horizontal rooftops still applies. At higher economic potentials the reduction of potential for the same CAPEX is approximately 10%. For the sake of simplicity, only horizontal rooftops will therefore be considered.

While the full technical potential on Bali can be achieved at an LCOE of 0.063 USD/kWp for a CAPEX of 600 USD/kWp, more electricity than the yearly demand of Bali can already be produced for a higher CAPEX. For example, 96% of the technical potential can be generated economically at a CAPEX of 650 USD/kWp, which is approximately equal to the CAPEX in India [50]. As total demand on Bali is approximately 5.7 TWh/year, sufficient electricity can be generated at or below the BPP for a CAPEX of approximately 830 USD/kWp. To achieve this, RTSVP panels are installed only at the most optimal locations. However, the CAPEX for RTSPV installations is currently far higher at an estimated 1200 USD/kWp. As can be seen in Figure 28, the economic potential of RTSPV is approximately 20 TWh/year for this CAPEX at an LCOE of 0.1 USD/kWp. For consumers — for whom RTSPV electricity replaces grid sourced electricity costing 0.1 USD/kWh — RTSPV generated electricity costing less than 0.1 USD/kWh is theoretically economically attractive. However, this assumes that the value of RTSPV electricity is independent of time of day. This is currently not the case, as PLN only pays 65% of the electricity price for electricity that is supplied to the grid. The effects of this discounting (the 'refund factor') will be explored further in Section 5.3.3.

5.3.3 Economic performance of individual residential and commercial RTSPV installations

Section 5.3.2 showed that RTSPV has currently achieved parity with the consumer electricity price on most of Bali. However, due to the fact that electricity generated with an RTSPV installation that is delivered to the grid only yields 65% (the 'refund factor') of the electricity price, there is a difference in value between RTSPV generated electricity that is immediately consumed by the owner (self consumption), and electricity that is not immediately consumed and sold to the grid. In order to determine the effect of this value difference, the self consumption rate of the owner of an RTSPV installation has to be known. The self consumption is dependent on the specific electricity demand profile of a consumer, and on the generation profile of the RTSPV installation. While the generation profile can be modeled for Bali and scaled to the capacity of the RTSPV installation — as has been done as part of the technical potential calculation in Section 5.2 — the demand profile is unique to every customer. As a result, the rate of self consumption is unique to every customer. The annual income from an RTSPV installation can be calculated with Equations 20-22 introduced in Section 5.3. It should be noted that the annual income of an RTSPV installation is not a net profit, it is actually a discount on the total annual electricity cost in case no RTSPV installation were installed. In theory it would be possible to generate a net income from an RTSPV installation if its capacity is greater than the consumption, but PLN does not allow for this (personal communication with GBPN, May 2022).

Demand profiles for individual households or other types of consumers are not available for Bali. To estimate the self consumption of a household, an assumed model household demand profile has been modeled in Appendix B. It is based on the estimated hourly power demand of common household appliances. This demand profile is assumed to be consistent for the entire year. The demand and generation profiles for a typical day are plotted in Figure 30. This demand profile results in a self consumption of 27%. The model household has a yearly electricity consumption of 26.7 kWh. Assuming the weighted average PV potential on Bali of 1500 kWh/kWp/year, an RTSPV installation with a capacity of 18 kWp is required to generate the same amount of electricity as the household consumes. The CAPEX of this RTSPV installation will be 21600 USD, assuming 1200 USD/kWp. The OPEX will be 180 USD/year, based on 10 USD/kWp/year average OPEX. The income — from avoided costs and supplying to the grid, minus OPEX — will be 1821 USD/year, assuming an electricity price of 0.1 USD/kWh and a refund factor of 65% using Equations 20-22. The annual ROI of this RTSPV, using Equation 17, is 8.4%. The payback period (PBP) of this installation will be 12 years. However, these calculations for the ROI and the PBP do not take the time value of money into account. As the discount rate is assumed to be 10% for Indonesia [46], this should be taken into account. Assuming a lifespan of 20 years, the internal rate of return (IRR) of this installation is 5.6%. This is lower than the discount rate, and does therefore indicate that this RTSPV installation is not actually a profitable investment. This is confirmed by the net present value (NPV) of this model RTSPV installation, which is -6020 USD over 20 years. This negative NPV indicates that RTSPV on Bali under current circumstances is not economically viable. While the RTSPV system analyzed here is large, the economic viability does not change for a smaller system size. The IRR is independent of system size. As a result, while the magnitude of the NPV for a smaller system size with otherwise the same input parameters is smaller, it is still negative. For example, an RTSPV system with a capacity of 3 kWp will have an IRR of 5.6% and an NPV of -1000 USD over 20 years.

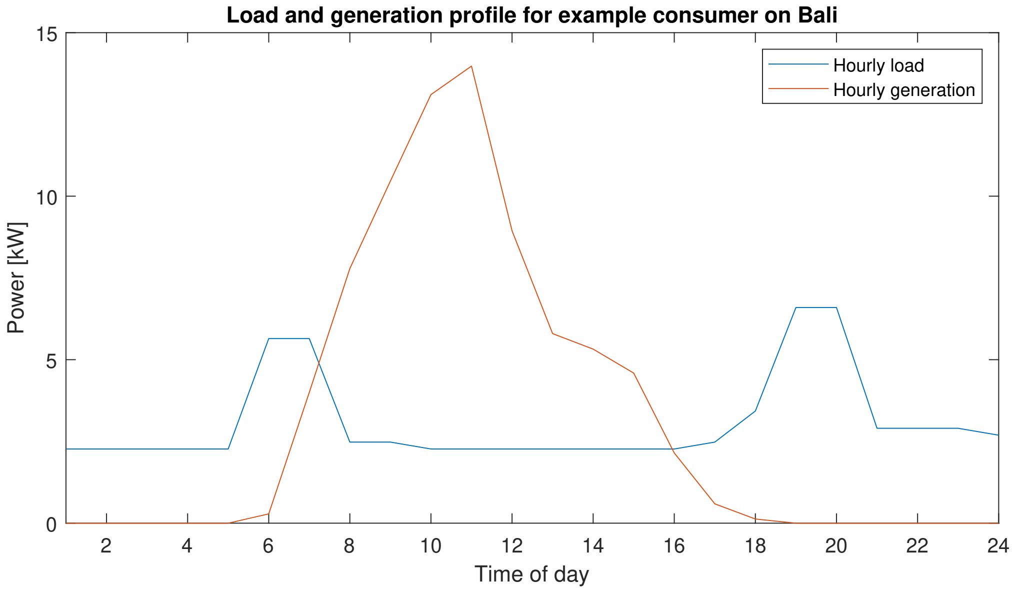

Figure 30: The demand and generation profiles for the model household on a typical day, base case.

Of the three factors that have the largest impact on the economic performance of an RTSPV installation at a given location — the PV potential of the location, CAPEX and self consumption — only the PV potential is essentially fixed. After all, the irradiance a solar module receives is location dependent save for some optimization regarding orientation and shading. This leaves CAPEX and self consumption as two factors that can potentially be changed, be it an exogenous change in CAPEX or an endogenous change in self consumption. To assess the required CAPEX and self consumption that ensure economic viability of an RTSPV installation the IRR can be calculated as a function of CAPEX and self consumption, shown in Figure 31. The plots show that at the current CAPEX of 1200 USD/kWh, the IRR will never exceed the discount rate of 10%, meaning that even if self consumption is at 100% the RTSPV installation will never generate a profit. For a self consumption rate of 27%, the CAPEX has to decrease to approximately 870 USD/kWp to ensure an IRR of 10%. If the self consumption of the model household is increased to 39% (see Figure 32), the CAPEX should be approximately 910 USD/kWp at most. Another option to increase the self consumption rate is to install an RTSPV installation with a lower capacity. If an RTSPV installation with a capacity of 9 kWp instead of 18 kWp is installed at the example household, the self consumption increases to 47%. However, if lower capacity RTSPV installations are installed than required to produce all the electricity consumed by a household, it is impossible to generate sufficient electricity through RTSPV to fully replace other electricity sources, essentially reducing the technical and economic potential. A higher self consumption allows for a higher CAPEX, and vice versa for a lower self consumption. A higher grid electricity price will also make RTSPV more competitive, but increasing the electricity price with the goal of making RTSPV more economically attractive is not a recommended solution.

Figure 31 can also be used to assess the effect of a different discount rate by looking up the required CAPEX and self consumption for an IRR equal to the new discount rate. For example, were the discount rate to decrease to 7.5%, a CAPEX of 1000 USD/kWp and a self consumption of 20% would allow the RTSPV installation to be economically viable. Additionally, Figure 31 can show the effect of increasing the refund rate to 1, in other words the effect of PLN paying 100% of the consumer electricity price rather than 65%. This would be identical to a self consumption rate of 100%, because in both cases the value of RTSPV electricity is equal to the full consumer electricity price. If the refund rate increases to 1, the IRR for a CAPEX of 1200 USD/kWp increases to approximately 10%, allowing for break even over the 20 year life span of the RTSPV installation.

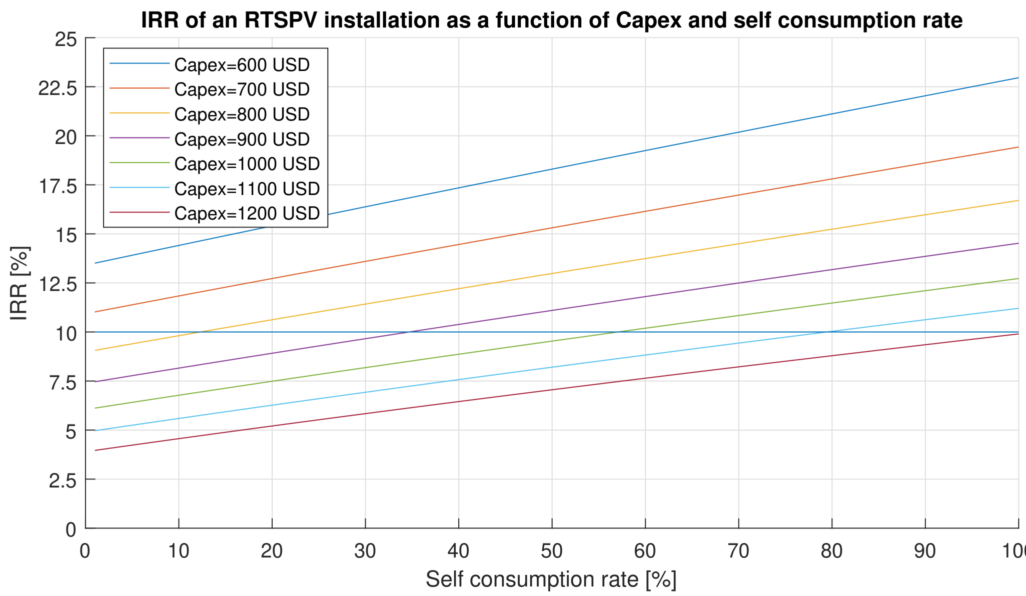

Figure 31: IRR of a residential RTSPV installation as a function of CAPEX and self consumption assuming a PV potential of 1500 kWh/kWp/year and a grid electricity price of 0.1 USD/kWh.

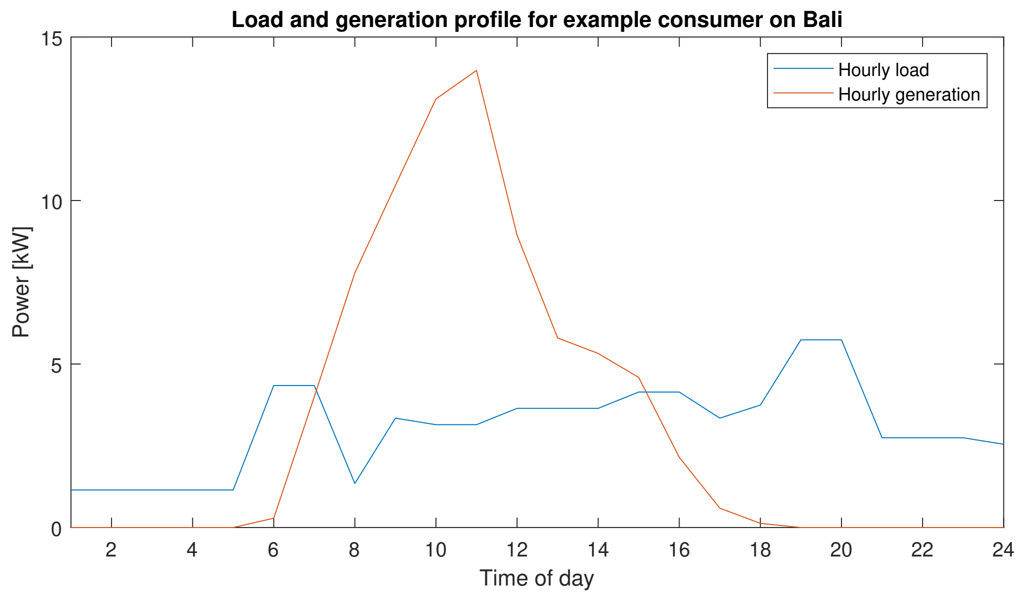

Figure 32: The demand and generation profiles for the model household on a typical day, increased self consumption rate.

Section 5.3.2 showed no economic potential for RTSPV for commercial customers at the current CAPEX of 1200 USD/kWp. This is confirmed in Figure 33, where the IRR for commercial RTSPV installation is much lower than for residential installations at the same CAPEX and self consumption. For commercial RTSPV installations to become profitable, CAPEX needs to reduce to below 700 USD for a self consumption rate of 50%. However, commercial customers can have a different demand profile than residential customers as more activity may be during the day rather than in the morning and at night. As a result, some commercial customers might have a much higher self consumption rate, improving the economic potential of an RTSPV installation. Alternatively, a different business model could be more viable for (larger) commercial RTSPV customers. Since the commercial electricity price assumed here is only 0.0127 USD/kWh higher than the BPP, and even lower than the BPP for some commercial customers, it can be more profitable to sell RTSPV electricity directly to PLN at the BPP. Commercial RTSPV installations thereby become IPPs. In this business model the limitation of the 65% refund rate is circumvented. As can be seen in Figure 28, this does require a CAPEX reduction to at least below 900 USD/kWh for commercial rooftops with the highest PV potential.

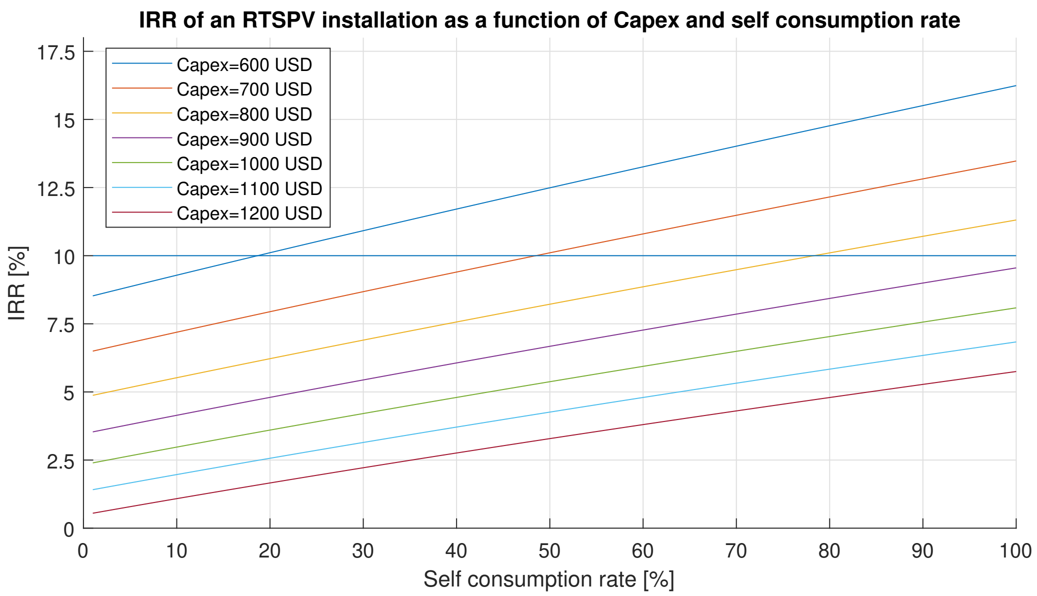

Figure 33: IRR of a commercial RTSPV installation as a function of CAPEX and self consumption assuming a PV potential of 1500 kWh/kWp/year and a grid electricity price of 0.075 USD/kWh.

5.3.4 Sensitivity analysis of economic potential

A sensitivity analysis is performed on the LCOE and the IRR. The LCOE is chosen as it is the most suitable parameter for comparisons with other sources of electricity, and the IRR because it directly indicates the economic viability of an RTSPV installation given a specific discount rate: if the IRR is higher than the discount rate, the investment will generate a positive return. The sensitivity analysis is performed by varying the input parameters for the LCOE and IRR calculations by +20% and -20% and observing the resulting relative change in the calculated LCOE and IRR.

LCOE The factors that have an impact on the LCOE of an RTSPV installation are the annual PV potential, the investment costs (CAPEX), annual maintenance costs, and the annual discount rate. The sensitivity of the LCOE to the variation of these factors is calculated by varying reducing and increasing each parameter individually by 20%. The results of the sensitivity analysis, depicted in Figure 34, indicate that the LCOE increases as CAPEX, maintenance costs, and the discount rate increase. The LCOE decreases as the annual PV potential increases. The variation of the LCOE as a result of the variation of each parameter is depicted as a relative deviation of the LCOE compared to the base case LCOE. The base case LCOE is 0.09 USD/kWh, which is the LCOE that results from a PV potential of 1500 kWh/kWp/year and a CAPEX of 1200 USD/kWh.

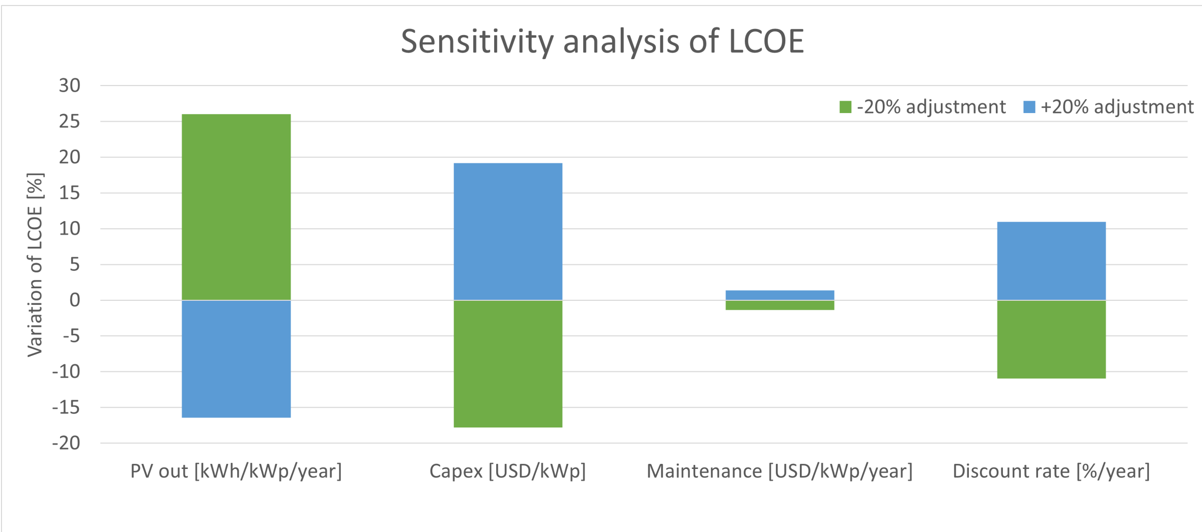

Figure 34: Sensitivity analysis of the LCOE compared to the base case.

IRR The IRR is, in addition to PV potential, CAPEX, and OPEX, also sensitive to the grid electricity price, the rate of self consumption, and the refund factor (Figure 35). The sensitivity of the NPV to the variation of these factors is calculated by varying reducing and increasing each parameter individually by 20%.

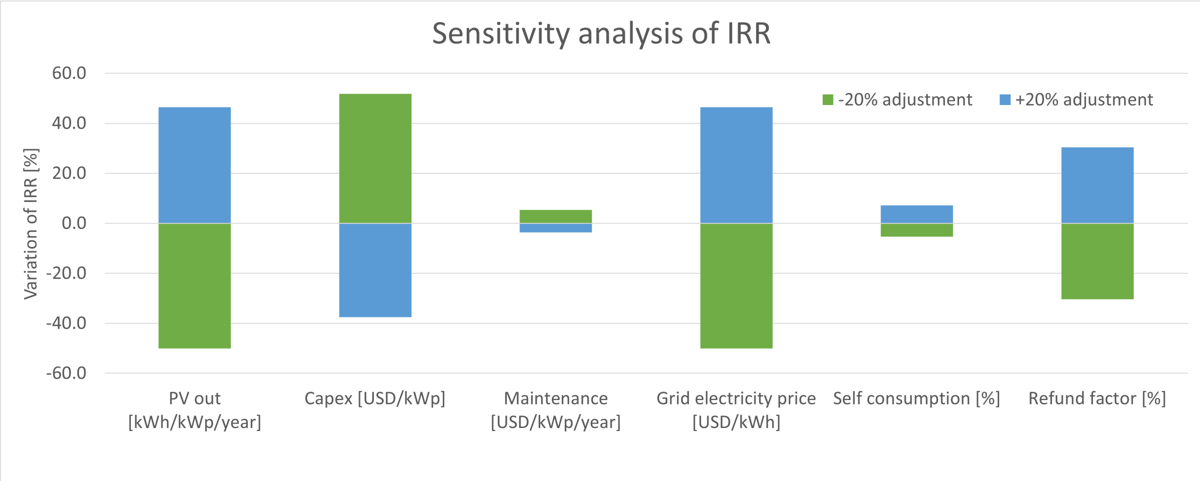

Figure 35: Sensitivity analysis of the IRR compared to the base case.

The IRR increases as the PV potential, grid electricity price, self consumption rate and the refund factor increase, and it decreases as the CAPEX and OPEX increase. This supports the findings in Section 5.3.3.

5.3.5 Policy options

In Section 5.3.3 the economic performance of a residential RTSPV installation was modeled. It was shown that, while the LCOE of RTSPV is lower than the price of grid electricity, an actual RTSPV installation will nevertheless generate a loss over its lifespan. The reason is the fact that PLN refunds only 65% of the consumer price for electricity that is supplied to the grid by a residential RTSPV installation. For a residential RTSPV installation to become profitable — meaning that the IRR exceeds the discount rate — the CAPEX needs to decrease to below 900 USD/kWp for a self consumption rate of 35%, a discount rate of 10% and a PV potential of 1500 kWh/kWp/year. For a consumer with a lower self consumption rate of 20%, the CAPEX should be no higher than 830 USD/kWp [Figure 31. If the price PLN pays for electricity that is supplied to the grid to 100% of the consumer electricity price, RTSPV installations can become economically viable at a CAPEX of 1200 USD/kWp. This represents the main policy recommendation, as it alone can make RTSPV economically viable.

Other options to increase the economic potential of RTSPV are centered around the other parameters that influence the IRR: reducing CAPEX, reducing the discount rate, increasing the self consumption rate and increasing the PV potential. The first two can potentially be achieved through subsidies, either on the purchase price of RTSPV components or through a government subsidized lowered interest rate on RTSPV related loans. Feed-in tariffs can also be implemented to directly subsidize RTSPV electricity. Reducing the CAPEX of RTSPV installations through subsidies can potentially have a snowball effect where the resulting market growth of RTSPV induces better economies of scale, further reducing CAPEX. As the unsubsidized CAPEX thereby decreases to below 900 USD/kWp — the maximum CAPEX for which RTSPV is estimated to be economically viable — government subsidies can be gradually reduced.

While such policies can have a positive impact on the economic potential of RTSPV, they will have to be financed in some way by the Indonesian government. As it stands, the government budget is already under considerable strain from existing subsidies on (fossil) energy [8]. In order to finance RTSPV subsidies, subsidies on other energy sources might have to be reduced which will raise energy prices for those without RTSPV installations. This can also be positive for RTSPV, as higher electricity prices will improve the IRR of RTSPV. This ties into another policy option that can indirectly increase the economic potential of RTSPV, the taxation of fossil energy sources, potentially through a carbon tax. There are myriad ways to apply such taxes, which are beyond the scope of this thesis. However, they are expected have globally the same outcome as a reduction of fossil energy subsidies, being price increases of fossil energy sources and therefore the electricity price.

The self consumption rate can partially be increased by running appliances only when RTSPV electricity is available where possible. Alternatively behind-the-meter batteries can be installed. However, these will add to the the price of RTSPV installations. Lastly, the PV potential is location dependent, but care can be taken to maximize the irradiance on RTSPV installations through strategic positioning.

A policy option that is not directly related to any of the economic parameters of RTSPV is mandating standards for the energy consumption of buildings. RTSPV can then become an attractive option to reduce the effective energy consumption of a building. However, this does not immediately improve the economic factors surrounding RTSPV, while potentially significantly increasing costs for building owners. Another option is to support the domestic manufacturing of PV components. While it is not guaranteed that it will immediately reduce the cost of RTSPV components, it will support the local economy and reduce the value of goods that need to be imported.

Another topic that should be addressed is the subject of the Local Content Requirement (LCR), which states that 50% of the parts of utility scale solar PV installations must be produced domestically. However, this does not apply to residential scale RTSPV installations[51] (personal communication with GBPN, May 2022). However, not all RTSPV is by definition residential, as RTSPV can also be mounted on commercial buildings. It is unclear if the LCR applies to commercial customers.

5.3.6 Economic potential conclusion

The estimation of the total economic potential in Section 5.3.2 showed that at current estimated RTSPV prices of 1200 USD/kWp approximately 20 TWh/year can be generated at or below the current consumer electricity price of 0.1 USD/kWh. This represents 87% of the estimated total technical potential of 22.9 TWh/year. However, when the BPP — which represents the costs of generating electricity through conventional methods — is taken as a reference, the economic potential of RTSPV drops to zero. In order for RTSPV to start competing with conventional sources of electricity, the CAPEX is required to decrease to less than 900 USD/kWp. In order for the economic potential to reach 96% of the full estimated technical potential at the BPP of 0.0623 USD/kWh RTSPV CAPEX should reduce to 650 USD/kWp, which is approximately equal to the CAPEX for RTSPV in India [50]. RTSPV does not necessarily need to directly compete with conventional generation methods, however. For residential consumers RTSPV can replace electricity otherwise bought from the grid at the higher price of 0.1 USD/kWh. If the consumer electricity price is taken as a reference, 20 TWh/year of the total technical potential of 22.9 TWh/year can be generated economically at the current CAPEX of 1200 USD/kWp. However, due to the refund rate of 65%, actual RTSPV installations will not be profitable at this CAPEX. It was shown in Section 5.3.3 that the CAPEX needs to reduce to below 900 USD/kWp for actual RTSPV installations to start becoming profitable. As the electricity price for commercial customers is lower than for residential customers, at 0.075 USD/kWh, it is even harder for RTSPV to compete with grid electricity for commercial customers. A reduction of CAPEX to at least below 700 USD/kWp is required for commercial RTSPV installations to become profitable if the same business model is applied as for residential RTSPV installations. A potentially better business model for commercial RTSPV installations is to sell generated electricity directly to PLN at the BPP. This can potentially be profitable at a CAPEX of 900 USD/kWp and below.

The main policy recommendation is to increase the refund rate from 65% to 100%. This will have the largest immediate impact on the economic potential of residential RTSPV as it ensures RTSPV installations will be profitable at the current CAPEX of 1200 USD/kWp. Other policy options include subsidies on the CAPEX of RTSPV installations to reduce investment costs, and subsidized loans to finance RTSPV installations for lower interest rates. Increasing the cost of grid electricity through reducing subsidies on fossil fuels, or through implementing an emissions tax will also have a positive effect on the economic potential of RTSPV as it will become a comparatively cheaper electricity source. Regulations that mandate lower net electricity use for buildings can also increase the market of RTSPV. Lastly, increasing support for domestic production of RTSPV components can have a positive effect on the local economy and reduce Indonesia's trade deficit. All of these policy options will have associated costs and other consequences, but their analysis is beyond the scope of this thesis.

5.4 Comparison to other research

In Section 2 a number of publications have been introduced that have also considered the technical potential of RTSPV on Bali, or proposed methodologies that are applicable to Bali. In this section a comparison will be made between the results of those publications and the results found in this thesis. The estimates are summarized in Table 5.

The institute of Essential Services Reform has estimated the total potential capacity to be 7.7 GWp at a utilization factor of 60% and with 330 Wp modules. Only the brand of the solar modules used is stated, which is Trina Solar, but no other specifications are provided. The specifications of the 330 Wp solar module currently on offer by Trina Solar specify a size of 1690mm by 996mm[52], which is similar to the dimensions of the SunPower X22-370 module used in this thesis. For the purpose of this comparison, it is assumed that the power density of both modules can simply be scaled based on their respective capacities. Scaling the 7.7 GWp IESR estimate to the 63% utilization factor and 370 Wp modules, the resulting capacity is 9.1 GWp.

Comparison of results with other publications			
Author	Rooftop area	Annual yield	Installable capacity
Koelewijn (2022)	130 km^2	22.9 TWh/year	17.9 GWp
IESR [21]			9.1 GWp (residential only)
IEA [13]	72.4 km^2	17.3 TWh/year	
Jacobson et al. [12]	123 km^2		
Joshi et al. [43]	97 km^2		

Table 5: Comparison of results found in this thesis with other publications concerning Bali.

The International Energy Agency has proposed a general formula to estimate total rooftop area and electricity yield in a locality based on population density[13, 23], described by Equations 17-20.

$$A_{capita} = \alpha * \rho^{-\beta} \tag{23}$$

$$A_{Bali} = A_{capita} * P_{Bali} \tag{24}$$

$$\eta = \eta_{BoS} * \eta_{module} \tag{25}$$

$$E_{PV,IEA} = A_{Bali} * G_M * \eta * AF * f_{orientation} \tag{26}$$

α and β represent constants defined as $\alpha = 172.3$ and $\beta = 0.352$ by IEA (2016)[13, 23]. The population density $\rho_{Bali} = 750/km^2$ and the total population $P_{Bali} = 4414000$. Efficiencies $\eta_{BoS} = 0.9$ and $\eta_{module} = 0.211$ as calculated in Section 5.2. Module irradiance $G_M = 2000kWh/m^2/year$ based on a horizontally mounted unshaded module as in Figure 22. utilization factor $AF = 0.63$ as defined in Section 5.2, and $f_{orientation} = 1$. As a result, the rooftop area per capita$A_{capita} = 16.8m^2$, total rooftop area on Bali$A_{Bali} = 72.4km^2$ and the total RTSPV annual electricity yield $E_{PV,IEA} = 17.3TWh/year$.

Jacobson et al. [12] has calculated the total rooftop area for all of Indonesia to be 7802 km^2. However, their methodology for Indonesia specifically is unclear, and it is therefore not possible to apply it to Bali directly. In order to make a comparison with the results of this thesis, the total rooftop area of Indonesia has been scaled based on the population ratio of Bali and Indonesia. The population of Bali is 4.4 million, and that of Indonesia is 273.5 million [53]. The resulting ration is 0.0157. Multiplying 0.0157 with 7802 km^2 results in an estimated 123 km^2 rooftop area for Bali. Joshi et al. [43] also calculated a total rooftop area for all of Indonesia, being 6163 km^2. Multiplying this with the population ratio of 0.0157 results in an estimated rooftop area of 97 km^2 for Bali.

All of the results summarized in Table 5 differ significantly from the results found in this thesis, with the exception of Jacobson et al. However, all of the estimations are of the same order of magnitude. The discrepancy can largely be explained by the fact that the results found in literature are based on low spatial resolution estimation methodologies, and are not intended for the sub-national scale of Bali. The discrepancy between IESR and the results found in this thesis can additionally be explained with the fact that IESR only considers residential rooftops. While the exact distribution between residential and commercial building areas on Bali is unknown, including commercial buildings would likely put the result closer to 130 km^2. Regarding IEA (2016), their model is supposed to apply to the entire world, and can therefore not be accurate on the scale of Bali. Similar discrepancies between rooftop areas estimated with the IEA methodology and reality were found by Castellanos et al. [23]. Additionally, since Jacobson et al. [12] and Joshi et al. [43] calculate rooftop areas on a national scale, their results are not by default representative on a sub-national scale either.

When comparing the economic potential found in this research to Putrano et al. [6], Putrano et al. concludes that RTSPV has achieved grid parity, in that the LCOE of RTSPV is lower than that of the consumer electricity price. This is confirmed in Section 5.3. However, Putrano et al. does not consider the IRR of RTSPV installations over their life time. In Section 5.3.3 it was found that the IRR of realistic RTSPV installations is currently lower than the discount rate. As a consequence RTSPV is currently not economically viable, even though the LCOE is lower than the consumer electricity price.

6 Discussion and conclusion

6.1 Discussion

In this chapter, certain limitations to the research conducted in this thesis are discussed in 6.1.1. In Section 6.1.2 a number of recommendations for future research will be given. Finally, the overall conclusions of this thesis are discussed by means of revisiting the main research question and research sub-questions in Section 6.2.

6.1.1 Limitations of methodologies used

Spatial resolution The spatial and weather data used in this research has a of 100m x 100m for the built-up area density data, and 250m x 250m for the PV potential data. The data used and the methodology used make that the calculation of rooftop area is of a medium-level spatial resolution [29]. While methodologies of this resolution are commonly used at scales similar to Bali, the accuracy is lower than high-level spatial resolution methodologies. The building footprint data from OSM, where present, has been shown to likely understate the actual building footprint area by 25% (Appendix A). In addition, the Copernicus built-up area density data and the Solargis PV potential data both have potential errors that directly translate to the technical and economic potential estimates. The consequence of the MEA and RMSE of the Copernicus data has not been quantified. However, deviations of the building footprint area calculated with the RAC methodology from the actual building footprint area in that region (the overshoot) can be adequately correlated with the average built-up area density in a region.

Limitations regarding the calculation of the technical potential The key assumption in the calculation method for rooftop area is that the footprint area of a building translates directly to the horizontal rooftop area. While it is unlikely that this assumption has a large negative impact on total technical and economic potential — given the large potential RTSPV overcapacity compared to total demand on Bali as identified in Section 5.2 — it is still an imperfect assumption. Secondly, technical potentials were calculated for either horizontal roofs and RTSPV installations, or roofs and RTSPV installations tilted at 30°. This assumption approximates the geometry of average rooftops on Bali, but it is not necessarily applicable to each individual roof. The estimated utilization factor of 63% is based on rectangular hip roofs with four elements, and it does not take more complex geometries into account. Additionally, the methodology assumes that every rooftop on Bali is suitable for the installation of RTSPV installations. This has not been verified. However, given the large overcapacity found, it is unlikely to be of significant consequence. Additionally, the solar modules used to calculate the technical potential, the SunPower X22-370, might not be available in Indonesia, as current solar module offerings appear to be of lesser quality (personal communication with GBPN, June 2022). However, technological development is ongoing, and it is assumed that solar modules available in Indonesia, by the time that a significant amount of RTSPV installations is being installed, will have improved in efficiency to at least the level of the SunPower X22-370. Also no consideration has been made for the proposed inverter limit of 15% of the connection capacity of the building on which the RTSPV installation is installed (personal communication with GBPN, May 2022). Accounting for this limit would theoretically lower the technical potential of RTSPV to only 15% of total electricity consumption on Bali at most.

Simplified economic analysis A number of generalizations have been made regarding the economic analysis. The first is the assumed linear pricing model of RTSPV installations. Especially for smaller installations, that are more likely to be found on residential roofs, this does not necessarily apply [49]. The discount rate used is also based on an assumption. The discount rate has a considerable impact on the LCOE and NPV of an RTSPV installation, as found in Section 5.3.4. If the actual discount rate in Indonesia is different, the effect on the economic potential can be significant.

No considerations for grid limitations As electricity generated with RTSPV does not follow demand, and no storage is implemented, high penetration of RTSPV has the potential to cause reverse power flows in the grid, and other types of grid instability [39]. Possibly, the inverter limit of 15% was implemented due to such stability concerns. In order to achieve the technical potential of RTSPV on Bali, the electricity grid has to be improved to handle the effects of high RTSPV penetration levels. This adds to the cost of RTSPV, but this is not considered in the economic analysis in Section 5.3. Another option to alleviate grid loading is behind-the-meter energy storage, where generated electricity is stored without loading the grid [39], but this option has not been explored technically or economically.

6.1.2 Recommendations for future research

Rooftop area While the RAC methodology was proven to deliver accurate results, the efficacy of the methodology on Bali is not directly verified. The reason for this is that the only possibility to measure the accuracy of the RAC methodology with a high degree of certainty is to compare the outcome to the actual building footprint area on Bali. However, this is not available, which is the reason the RAC methodology was developed in the first place. In lieu of that, more validations on areas with complete building footprint data — such as in Section 4 — can be performed to gain further understanding of the behaviour of the model. In addition, the exercise of manually removing building footprint data such as in Section 4.4 can be repeated to further understand the effect of the type of data incompleteness found on Bali.

Technical potential The methodology to calculate the technical potential of RTSPV on Bali makes a number of generalizations to compensate for missing data, mainly regarding weather data and actual rooftop geometry data. If more complete and higher resolution weather data is used, a more accurate calculation of solar irradiance and overall yield can be made. Additionally, more detailed data of individual roof geometry allows for a more accurate simulation of the technical potential for individual buildings. Additional research on grid considerations as RTSPV penetration increases can also be done.

Economic potential More accurate results in the technical potential calculation will improve the accuracy of the economic potential calculation. In addition, there are a number of factors that have a considerable influence on the LCOE and/or the IRR of RTSPV installations on Bali, as discussed in Section 5.3.4. These include the cost of RTSPV installations, the discount rate and the electricity demand profile. Gathering more data on these factors will allow for a more accurate calculation of the Economic potential. The effect of including storage systems such as batteries can also be researched. A number of policy options to increase the economic potential of RTSPV has been given in Section 5.3.5, and more research can be done on the actual economic effects of these policies. The potential business model of commercial RTSPV installations selling directly to PLN and thereby becoming IPPs can also be explored further.

6.2 Conclusion

In this section the research sub-questions and the main research question posed in Chapter 1 will be directly addressed.

Sub-question 1: What is the total rooftop area on Bali? In Section 3.2, the RAC methodology was proposed that calculates the total building footprint area, and — by assumption — the total rooftop area, based on built-up area data from the Copernicus Global Land Service [33] and incomplete building footprint data obtained from OSM. The methodology was proven to be reliable in Section 4, where it was applied to areas with complete building footprint data and checked for convergence. Additionally, the impact of the variance of the underlying data was analyzed, and the RAC methodology was applied to areas with building footprint data made artificially incomplete. In Section 5.1 the total building footprint area, and by assumption the rooftop area, of Bali was calculated to be 130 km^2. The RAC methodology proposed in this research has not been used in research before. When considering the three levels of technical potential calculation methodologies discussed in Section 2, the RAC methodology is a medium-level methodology. It uses GIS based data on actual building footprints and built-up area density, and it allows for the use of incomplete data, which is unique.

Sub-question 2: What is the estimated technical potential of RTSPV on Bali? By using hourly solar irradiance and weather data, a model was constructed that simulates the yield of a SunPower X22-370 solar module on Bali based on its azimuth and tilt in Section 5.2. It was assumed that all rooftops on Bali are rectangular hip roofs with segments that are oriented at $90°$ to each other. Furthermore, due to the large number of rooftops, it was assumed that the azimuth of all rooftops is homogeneously distributed between $0°$ and $359°$. Using these assumptions, it was found that for increasing rooftop tilt — meaning that the tilt of each of the four segments of a rooftop increases — the average irradiance on the entire rooftop decreases. However, the total surface area of the rooftop will increase. Consequentially, the overall yield of a rooftop will increase for increasing tilt as proportionally more RTSPV modules can be installed. In addition, a shading model was constructed that estimates shading losses from a continuous obstruction around an RTSPV installation that blocks all light below a certain attitude. Based on this model, average shading losses were estimated to be 15.8%. The rooftop utilization factor was estimated to be 63%. Finally, using Solargis PV potential data, the total technical potential of RTSPV on Bali was found to be 22.9 TWh/year for horizontal rooftops, and 23.4 TWh/year for rooftops with segments tilted at $30°$, both including 15.8% shading losses and assuming a 63% utilization factor. The conservative estimate of 22.9 TWh/year of technical potential exceeds the estimated annual electricity consumption of Bali of 5.7 TWh/year by a factor 4.

Sub-question 3: What is the estimated economic potential of RTSPV on Bali? The total economic potential of RTSPV on Bali was calculated as a function of LCOE and CAPEX in Section 5.3.2. It was found that for a target LCOE of 0.063 USD/kWp — the LCOE at which RTSPV would achieve parity with conventional sources of electricity — the economic potential is zero above a CAPEX of 900 USD/kWp. If the CAPEX reduces further to 750 USD/kWp the economic potential is approximately 19 TWh/year, which represents 83% of the estimated total technical potential of 22.9 TWh/year. 96% of the full technical potential can be achieved at a CAPEX of 650 USD/kWp, which is approximately equal to the current CAPEX of RTSPV in India [50]. However, RTSPV does not necessarily need to directly compete with conventional generation methods. For residential consumers, electricity from an RTSPV installation can replace electricity otherwise bought from the grid at the higher consumer price of 0.1 USD/kWh. If this consumer price is taken as a reference, the current estimated CAPEX of 1200 USD/kWp is low enough to allow for an economic potential of 20 TWh/year. However, this assumes that the value of RTSPV electricity is independent of the time of day at which it is generated. This is not the case as any RTSPV electricity that gets sold to the grid only yields 65% of the consumer electricity price. When this is taken into account, the CAPEX should reduce to below 900 USD/kWp to ensure the IRR is higher than the discount rate for a residential RTSPV system with a self consumption rate below 35%. In conclusion, under current circumstances the CAPEX of RTSPV has to decrease to below 900 USD/kWp to both compete with conventional generation methods, and for residential RTSPV installations to become economically viable. For commercial customers the business model used by residential RTSPV customers performs worse economically due to the lower electricity price for commercial customers. For these customers a better business model might be to become an IPP by selling electricity directly to PLN at the BPP. This can become profitable at a CAPEX below 900 USD/kWp in areas with the highest PV potential, as the LCOE is equal to the BPP at that CAPEX.

Sub-question 4: How can the economic potential of RTSPV on Bali be increased? Factors that most influence the LCOE of RTSPV are the PV potential of the location where the RTSPV installation is installed, the CAPEX of the installation and the discount rate. The economic potential calculation already accounts for varying PV potentials. That leaves reducing the CAPEX and discount rate as options to increase economic potential. RTSPV prices have generally been decreasing over the years [50], and increasing economies of scale can potentially contribute to this reduction. To further decrease RTSPV costs subsidies on the CAPEX and/or interest rates can bring the LCOE down. Feed-in tariffs on RTSPV electricity can also be implemented to directly reduce the consumer cost of RTSPV generated electricity. For the economic potential individual RTSPV installations the grid electricity price, the refund factor and the self consumption rate are additionally of influence. If subsidies on fossil energy are reduced, electricity prices will increase and RTSPV will become more economically attractive. Reducing fossil energy subsidies also potentially frees up budget for RTSPV subsidies. Increasing the refund factor to 100% will make residential RTSPV installations economically viable at a CAPEX of 1200 USD/kWp and lower, and is therefore the main policy recommendation. Increasing the self consumption rate can be achieved through installing a lower capacity RTSPV installation and/or through implementing behind-the-meter electricity storage. However, if the capacity of RTSPV installations is reduced to below what is necessary to cover the electricity consumption of a household, RTSPV will never be able to fulfill the overall electricity demand of Bali. Behind-the-meter storage does not have this limitation, but it will add on to the CAPEX of an RTSPV installation, and it is beyond the scope of this thesis.

Main research question: What is the estimated technical and economic potential of rooftop solar photovoltaics on Bali, and how can these potentials be increased? In conclusion, the estimated technical potential for RTSPV assuming horizontal rooftops on Bali is 17.9 GWp, utilizing 63% of the estimated total rooftop area of 130 km^2, assuming a yield reduction of 15.8% due to shading, and resulting in an estimated yield of 22.9 TWh/year. If rooftops are assumed to consist of four segments that are tilted at $30°$, the estimated yield increases to 23.4 TWh/year. The yield figure of 22.9 TWh/year exceeds estimated electricity consumption on Bali by a factor 4. RTSPV is currently not cost competitive with the BPP, as no electricity can be generated at or below the BPP of 0.063 USD/kWh. In order to achieve 96% of the technical potential at or below the BPP, the CAPEX of RTSPV has to decrease from the current 1200 USD/kWp to less than 650 USD/kWp, a CAPEX similar to that of India. However, as residential RTSPV electricity competes with grid electricity priced at 0.1 USD/kWh rather than the BPP, residential RTSPV installations can become profitable for a CAPEX below approximately 900 USD/kWp. The main factors limiting the economic potential of RTSPV on Bali are the high CAPEX and the refund rate of 65%. The main policy recommendation is to increase the refund rate to 100% as this will make RTSPV installations generally profitable at the current CAPEX of 1200 USD/kWp. Other policy options are reducing the CAPEX through subsidies, or by subsidizing loans for RTSPV installations to ensure lower interest rates. Other options include reducing the subsidies on fossil energy, which will increase electricity prices making RTSPV more competitive.

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Appendix A Assessment of accuracy of OpenStreetMap on Bali

In this appendix the quality of the OpenStreetMap building footprint data will be assessed. First of all, A global overview of where OSM data is broadly missing is given. Secondly, the accuracy of OSM data that does exist is discussed.

Figure 36 gives a global overview of areas on Bali with missing OSM building footprint data. Areas on Bali that appear white should be built-up according to the Copernicus built-up area data. The OpenStreetMap building footprint data is overlaid over the built-up area density map. Any built-up area should therefore be obscured by the building footprints. Any areas that are white are therefore missing OpenStreetMap building footprint data. The areas with the most data missing are indicated by red boxes. In the top left corner, Copernicus mislabeled farmland as built-up area. This section is, however, not used to calculate total building footprint area.

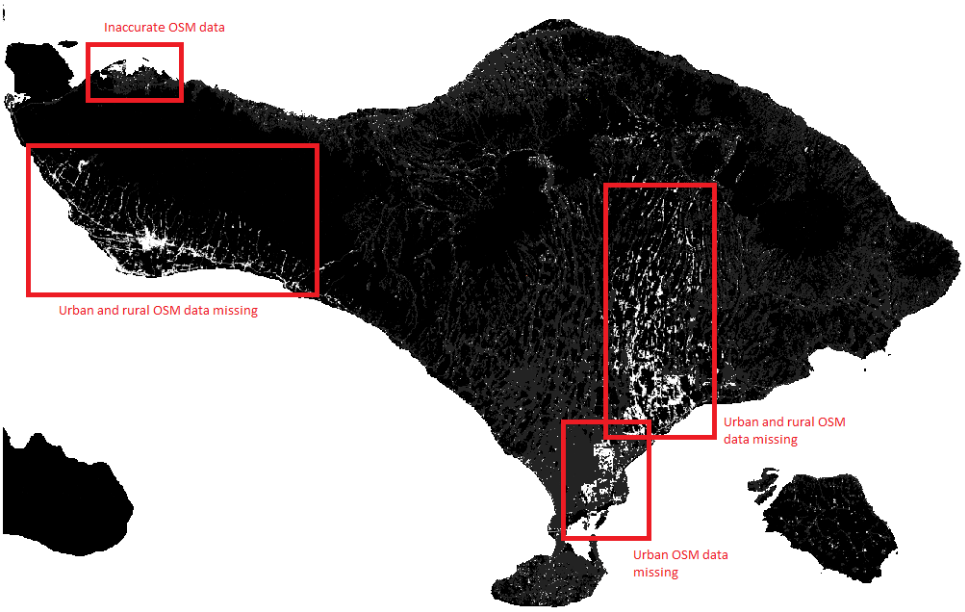

Figure 36: Global overview of missing OpenStreetmaps building footprint data.

Figures 37, 38, 39 and 40 represent examples of the match between OSM and satellite imagery from Google Earth. In these images, the OSM building footprint data is overlaid on satellite images. First of all, the OSM building footprints for each individual building generally do not cover the entire building. Secondly, there appears to be a consistent misalignment between OSM data and the buildings visible on the satellite images. This misalignment is of no consequence for the overall match between OSM building footprint area and real building footprint area, but the fact that the OSM building footprints are generally smaller than the buildings visible on Google Earth is of consequence. It has been estimated that the actual building footprints are generally 25% larger than the OSM building footprints that represent these buildings.

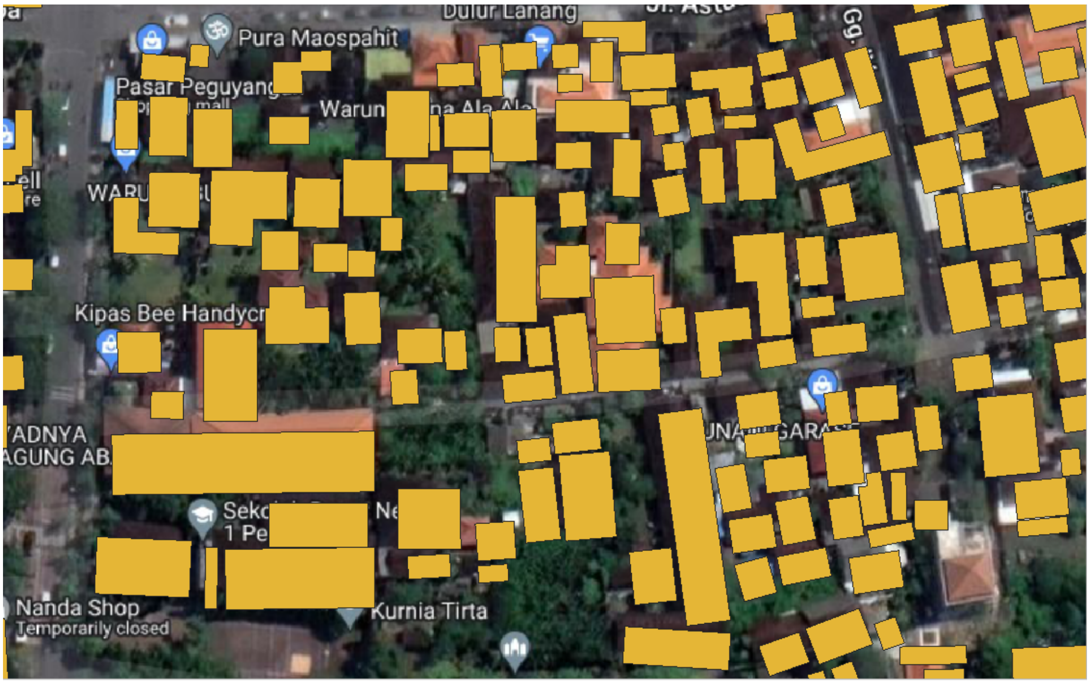

Figure 37: Example 1 of the match between OpenStreetMap and Google Earth

Figure 38: Example 2 of the match between OpenStreetMap and Google Earth

Figure 39: Example 3 of the match between OpenStreetMap and Google Earth

Figure 40: Example 4 of the match between OpenStreetMap and Google Earth

Appendix B Demand profiles used for model household

In this appendix the demand profiles used for the model household in Section 5.3.3 are given.

		ac	lights	cooking	fridge	pc	tv	laundry		ac	lights	cooking	fridge	pc	tv	laundry		Total (kW)
time	wattage	2000	200	3000	150	250	150	500										
1		1			1					2000	0	0	150	0	0	0		2.15
2		1			1					2000	0	0	150	0	0	0		2.15
3		1			1					2000	0	0	150	0	0	0		2.15
4		1			1					2000	0	0	150	0	0	0		2.15
5		1			1					2000	0	0	150	0	0	0		2.15
6		1	1	1	1					2000	200	3000	150	0	0	0		5.35
7		1	1	1	1					2000	200	3000	150	0	0	0		5.35
8		1	1		1					2000	200	0	150	0	0	0		2.35
9		1	1		1					2000	200	0	150	0	0	0		2.35
10		1			1					2000	0	0	150	0	0	0		2.15
11		1			1					2000	0	0	150	0	0	0		2.15
12		1			1					2000	0	0	150	0	0	0		2.15
13		1			1					2000	0	0	150	0	0	0		2.15
14		1			1					2000	0	0	150	0	0	0		2.15
15		1			1					2000	0	0	150	0	0	0		2.15
16		1			1					2000	0	0	150	0	0	0		2.15
17		1	1		1					2000	200	0	150	0	0	0		2.35
18		1	1		1	1	1	1		2000	200	0	150	250	150	500		3.25
19		1	1	1	1	1	1	1		2000	200	3000	150	250	150	500		6.25
20		1	1	1	1	1	1	1		2000	200	3000	150	250	150	500		6.25
21		1	1		1	1	1			2000	200	0	150	250	150	0		2.75
22		1	1		1	1	1			2000	200	0	150	250	150	0		2.75
23		1	1		1	1	1			2000	200	0	150	250	150	0		2.75
24		1			1	1	1			2000	0	0	150	250	150	0		2.55

Figure 41: Demand schedule for a model household with a self consumption of 27%.

		a/c	lights	cooking	fridge	pc	tv	Laundry		a/c	lights	cooking	fridge	pc	tv	laundry		Total (kW)
Time	wattage	2000	200	3000	150	250	150	500										
1		0.5			1					1000	0	0	150	0	0	0		1.15
2		0.5			1					1000	0	0	150	0	0	0		1.15
3		0.5			1					1000	0	0	150	0	0	0		1.15
4		0.5			1					1000	0	0	150	0	0	0		1.15
5		0.5			1					1000	0	0	150	0	0	0		1.15
6		0.5	1	1	1					1000	200	3000	150	0	0	0		4.35
7		0.5	1	1	1					1000	200	3000	150	0	0	0		4.35
8		0.5	1		1					1000	200	0	150	0	0	0		1.35
9		1.5	1		1					3000	200	0	150	0	0	0		3.35
10		1.5			1					3000	0	0	150	0	0	0		3.15
11		1.5			1					3000	0	0	150	0	0	0		3.15
12		1.5			1			1		3000	0	0	150	0	0	500		3.65
13		1.5			1			1		3000	0	0	150	0	0	500		3.65
14		1.5			1			1		3000	0	0	150	0	0	500		3.65
15		2			1					4000	0	0	150	0	0	0		4.15
16		2			1					4000	0	0	150	0	0	0		4.15
17		1.5	1		1					3000	200	0	150	0	0	0		3.35
18		1.5	1		1	1	1			3000	200	0	150	250	150	0		3.75
19		1	1	1	1	1	1			2000	200	3000	150	250	150	0		5.75
20		1	1	1	1	1	1			2000	200	3000	150	250	150	0		5.75
21		1	1		1	1	1			2000	200	0	150	250	150	0		2.75
22		1	1		1	1	1			2000	200	0	150	250	150	0		2.75
23		1	1		1	1	1			2000	200	0	150	250	150	0		2.75
24		1	1		1	1	1			2000	200	0	150	250	150	0		2.75

Figure 42: Demand schedule for a model household with a self consumption of 36%.