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Management, and decision-making tool for data of multiple photovoltaic microgenerators distributed in Brazil

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Abstract

The aim of this research was to develop a management and decision-making support tool to evaluate the energy yield of multiple solar photovoltaic (PV) systems installed on residential rooftops, connected to the same electrical distribution grid, and located in a decentralized way in a large territory, which makes them exposed to different levels of solar irradiation. To achieve this goal, the *CELESC Photovoltaic Bonus Program* was used as a case study, which was carried out under the Energy Efficiency Program of the CELESC utility, that supplies the state of Santa Catarina (SC), and operated in partnership with ENGIE Brasil Energia. This program aimed to encourage the generation of electricity through solar irradiation by the installation of PV systems in single-family homes. There were 1,250 identically equipped PV microgenerators with individual power of 2.65 kWp, distributed across SC and together amounting to about 3 MWp. In this context, the need to analyze large volumes of data quickly was identified, as well as to ensure the quality and significance of data from PV distributed generation (DG). For this, a technical-statistical algorithm was developed for the detection and discarding of microgenerators with faulty data. The exploration and strategic analysis of data through the implementation of Business Intelligence (BI) concepts, combined with this algorithm, allowed us to evaluate the yield of PV systems over the state of SC, providing relevant information about performance and helping to support decision making in a quickly and well-founded way. The results show irradiation maps in the tilted plane divided in four ranges (statistical quartiles) and, for the base year 2019, the values show, for the four different ranges in which the territory of SC was divided, with 95% reliability, annual average of daily energy yield of 3.35 kWh/kWp·day or 1,222 kWh/kWp·year (range 1), 3.74 kWh/kWp·day or 1,365 kWh/kWp·year (range 2), 3.82 kWh/kWp·day or 1,394 kWh/kWp·year (range 3) and 3.90 kWh/kWp·day or 1,423 kWh/kWp·year (range 4). The annual average of PV generation from each analyzed roof was 3,353 kWh/year (annual yield = 1,265 kWh/kWp·year). Another important and curious topic among researchers and the PV market has been the emergence of a new agent in the DG model: the prosumer (producer + consumer). This was the second front of studies addressed in this doctoral research, which aims to understand and analyze the roles and benefits of grid-connected PV microgenerators. To do this, a representative prosumer unit (PU) from the sample of 1,250 rooftops was analyzed and a method was developed to present the different perspectives involved in the operation of this market agent. From the utility's perspective, annual electricity consumption was reduced by 18% after the PV integration. From the PU's perspective, total annual consumption increased by 8%. However, **the annual reduction in electricity expenses was 54%**. The adoption of the PV rooftop in households in Brazil has proven to be advantageous and, moreover, the payback time is on a downward trend due to the continuous price reductions experienced by the PV technology. The methodology developed in this thesis can be used to predict the monthly or annual generation of future PV systems to be installed at any location for distributed generation asset allocation planning, as well as serving as a subsidy for more refined return on investment analyses.

Resumo

O objetivo desta pesquisa foi desenvolver uma ferramenta de gestão e apoio a tomada de decisão para avaliar a produtividade energética de múltiplos sistemas fotovoltaicos (FV), instalados sobre telhados residenciais, conectados à mesma rede elétrica de distribuição e localizados de forma descentralizada dentro de um grande território, o que faz com que sejam submetidos a diferentes níveis de irradiação solar. Para atingir esse objetivo, foi utilizado como estudo de caso o "Programa Bônus Fotovoltaico", que foi realizado no âmbito do Programa Eficiência Energética da distribuidora CELESC, que atende o estado de Santa Catarina (SC), e operacionalizado em parceria com a ENGIE Brasil Energia. Esse programa teve por objetivo incentivar a geração de energia elétrica através da irradiação solar por meio da instalação de sistemas FV em residências unifamiliares. Foram instalados 1.250 microgeradores FV com equipamentos idênticos, com potência individual de 2,65 kWp, distribuídos por SC e que juntos somam cerca de 3 MWp. Neste contexto, foi identificada a necessidade de analisar grandes volumes de dados de forma rápida, bem como de garantir a qualidade e significância de dados da geração distribuída (GD) FV. Para isso, foi desenvolvido um algoritmo técnico-estatístico para a detecção e descarte de geradores com dados falhos. A exploração e análise estratégica de dados através da implementação de conceitos *de Business Intelligence* (BI), aliada a esse algoritmo, permitiu avaliar a produtividade dos sistemas FV ao longo do estado de SC, proporcionando informações relevantes sobre sua performance e ajudando no suporte à tomada de decisão de forma rápida e embasada. Os resultados apresentam mapas da irradiação solar no plano inclinado divididos em quatro faixas (quartis estatísticos) e, para o ano base de 2019, os valores mostram, para as quatro diferentes faixas nos quais o território catarinense foi dividido, com 95% de confiabilidade, produtividade média anual de energia diária de 3,35 kWh/kWp·dia ou 1.223 kWh/kWp·ano (faixa 1), 3,74 kWh/kWp·dia ou 1.365 kWh/kWp·ano (faixa 2), 3,82 kWh/kWp·dia ou 1.394 kWh/kWp/ano (faixa 3) e 3,90 kWh/kWp·dia ou 1.423 kWh/kWp·ano (faixa 4). A média anual da geração FV do conjunto de telhados analisado foi de 3.353 kWh/ano (rendimento anual = 1,265 kWh/kWp·ano). Outro tema importante e de bastante curiosidade entre os pesquisadores e o mercado FV tem sido o surgimento de um novo agente dentro do modelo de GD: o prossumidor (produtor + consumidor). Essa foi a segunda frente de estudos abordada nesta pesquisa de doutorado, que objetiva entender e analisar os papeis e os benefícios de microgeradores FV conectados à rede elétrica. Para isso, foi analisada pontualmente uma unidade prossumidora (UP) representativa da amostra de 1.250 telhados e desenvolvido um método para apresentar as diferentes óticas envolvidas na operação desse agente do mercado. Do ponto de vista da concessionária, o consumo anual de energia elétrica foi reduzido em 18% após a integração FV na UP. Do ponto de vista da UP, o consumo anual total aumentou 8%. No entanto, **a redução anual das despesas com energia elétrica foi de 54%**. A adoção do telhado FV em residências no Brasil demonstrou ser vantajosa e, além disso, o tempo de retorno do investimento está em tendência de queda devido às contínuas reduções de preços experimentadas pela tecnologia FV. A metodologia desenvolvida nesta tese pode ser utilizada para prever a geração mensal/anual de futuros sistemas FV a serem instalados em qualquer local para planejamento de alocação de ativos de GD, além de servir de subsídio para análises de retorno do investimento mais apuradas.

RESUMO EXPANDIDO

Introdução

O avanço tecnológico e o anseio pela descarbonização são fatores que vem transformando mundialmente o setor de energia, mudando os meios tradicionais de geração e de consumo de eletricidade. O setor residencial contribui para impulsionar essa mudança, devido à utilização de dispositivos elétricos mais eficientes, bem como a integração de geradores solares fotovoltaicos (FV) e de baterias, impactando diretamente na geração, transmissão e distribuição da energia elétrica. As edificações são responsáveis pela maior parte do consumo de energia do mundo. Portanto, o conceito de edifício de energia zero (*Zero Energy Building* - ZEB) faz todo o sentido, pois, com a redução da demanda energética dos edifícios da rede da concessionária, reduz-se a necessidade de expansão e construção de grandes centrais geradoras para alimentar os centros urbanos.

Embora o Brasil apresente grande potencial para o aproveitamento da energia solar e a tecnologia FV disponível seja simples e de fácil uso, ainda há muito a ser feito para consolidar a geração solar FV na matriz energética, devido à existência de barreiras técnicas, econômicas, sociais, gerenciais e políticas. Entre as principais barreiras identificadas estão: a qualidade da instalação dos sistemas FV, o alto custo do investimento inicial, a dependência de financiamento para a aquisição de sistemas FV, o desconhecimento da tecnologia FV por parte do consumidor, os serviços de pós-venda, a dependência de importações de módulos FV da China e o contexto das políticas públicas para incentivar a GD FV.

Diante desse cenário de mercado promissor, mas com tantas barreiras a vencer, a análise do volume de dados de milhares de novos microgeradores tem sido uma tarefa árdua, uma vez que é comum que vários microgeradores apresentem dados falhos ocasionados por diversas causas e que carecem do uso de métodos confiáveis para a detecção e diagnóstico de falhas em sistemas FV. Esse fato torna necessário o desenvolvimento de mecanismos para o tratamento de dados operacionais de sistemas FV conectados à rede elétrica, já que monitorar remotamente a produção de energia FV por meio de sensores não é uma tarefa trivial e a aquisição desses dados deve passar por uma curadoria técnica minimamente qualificada. Atualmente existe uma carência de produção científica que aborde simultaneamente métodos técnicos e estatísticos para a análise e o tratamento de dados de microgeradores FV em grande escala.

Com o avanço da tecnologia da informação, bem como devido ao aumento da capacidade de coleta e armazenamento de dados, organizações vem buscando melhorias no processamento, visualização e interpretação de grande volume de informações, que são disponibilizadas diariamente. A velocidade e a variedade na coleta e armazenamento de dados aumenta rapidamente, por meio de recursos internos e externos. Essa demanda vem fazendo com que se adotem ferramentas de *Business Intelligence* (BI) para a análise crítica e gerenciamento de negócios de uma forma mais eficaz. O tema BI é muito utilizado em pesquisas de análise de dados e sistemas de apoio à decisão.

A importância do BI depende dos tipos de dados extraídos e de como eles são utilizados. O principal fator, no entanto, é o método de transformar dados brutos em informações valiosas, e não a quantidade dos dados. Portanto, a definição e validação de indicadores torna-se essencial para identificar o foco e os dados que serão coletados.

Uma metodologia adequada para avaliar múltiplos pontos de geração pode fornecer informações relevantes no que diz respeito à produtividade da geração FV ao longo das áreas onde esses sistemas foram instalados.

Apenas um microgerador FV já gera grandes volumes de dados operacionais brutos, mesmo em escalas com baixa resolução temporal. Para a análise de dados da malha distribuída de centenas de microgeradores FV, tornam-se necessários sua organização e seu armazenamento. Nesse contexto, surgem grandes desafios; entre eles, a integração e transformação de dados brutos em informações relevantes para o controle, gerenciamento e para o processo decisório.

A exploração e a análise estratégica de dados – através da implementação de conceitos de BI, aliada a um algoritmo baseado em métodos técnicos-estatísticos que permita avaliar a produtividade de sistemas FV – pode proporcionar aos gestores informações relevantes sobre o desempenho de tais sistemas e, assim, dar suporte à tomada de decisão de forma rápida e simples.

Nos anos de 2017 e 2018, no âmbito do programa "Bônus Fotovoltaico" da distribuidora local (Centrais Elétricas de Santa Catarina - CELESC), foram instalados 1.250 microgeradores FV idênticos com módulos fotovoltaicos de silício cristalino, conectados à rede elétrica em baixa tensão, com potência individual de 2,65 kWp, distribuídos ao longo do estado de Santa Catarina (SC) - Brasil, com potência total instalada de aproximadamente 3,3 MWp. Este trabalho se propõe a analisar, para o período compreendido entre janeiro e dezembro de 2019, a produtividade mensal e anual de múltiplos sistemas FV de microgeração distribuída usando aplicações inéditas de BI, intituladas *Energy Business Intelligence* (E-BI), aliadas a um algoritmo técnico-estatístico para avaliar a produtividade de tais sistemas. Os resultados são apresentados visualmente em mapas via GIS.

Do ponto de vista do consumidor, a microgeração distribuída representa economia nos custos de eletricidade. Com isso, nasceu um novo agente no cenário elétrico, o prossumidor (produtor + consumidor), interessado em investir na autogeração. A literatura carece de análises aprofundadas e de métodos para avaliar o papel e os benefícios desse novo agente (prossumidor) no contexto da GD. Portanto, este trabalho tem como objetivo avaliar, sob a ótica da concessionária e a ótica do prossumidor, os impactos técnico-econômicos proporcionados pela adoção da geração FV. Para isso, foi desenvolvido um estudo de caso em uma residência contemplada pelo projeto "Bônus Fotovoltaico" com uma metodologia para avaliar, sob essas diferentes perspectivas, os impactos da adoção da geração solar FV nas residências no contexto da regulação do mercado elétrico brasileiro.

Objetivos

O objetivo desta pesquisa foi avaliar a produtividade de um grande conjunto de sistemas fotovoltaicos no estado de Santa Catarina por meio de uma ferramenta de gestão e auxílio à tomada de decisão, que possibilita a análise, com eficiência e eficácia, de um grande volume de dados de microgeradores fotovoltaicos conectados à rede de distribuição de forma descentralizada. Para alcançar o objetivo geral da tese, foram estabelecidos os seguintes objetivos específicos:

- Obter banco de dados dos 1.250 microgeradores distribuídos que foram contemplados no PEE da CELESC (Bônus FV) e que foram instalados ao longo do Estado de SC;
- Obter banco de dados de satélite com registros históricos de irradiação solar ao longo do Estado de SC;
- Dividir o Estado por regiões, conforme faixas irradiação mensais e anuais;
- Mapear a localização dos geradores FV dentro do Estado de SC;
- Usar conceitos de *Business Intelligence* (BI) para a análise e gestão da informação;
- Desenvolver algoritmo técnico-estatístico para filtrar, analisar e validar uma amostra confiável de microgeradores;
- Analisar a produtividade de microgeradores FV instalados em regiões distintas ao longo do Estado de SC;
- Simular produtividade teórica, baseada em bancos de dados de satélite, para cada unidade microgeradora em estudo;
- Comparar produtividades teórica e medida para cada microgerador da amostra;
- Desenvolver ábaco de produtividade FV para o Estado de SC, com indicadores estatísticos e mapeamento por faixa de irradiação;
- Apresentar a análise energética detalhada de uma das unidades prossumidoras da amostra;
- Apresentar os impactos socioeconômicos do Prossumidor, o novo agente no mercado de GD.

Método

Nos 12 meses de 2019, no âmbito deste trabalho, foram medidos dados de geração FV (em intervalos de 5 minutos) de 1.250 microgeradores (idênticos) com potência instalada de 2,65 kWp por unidade, monitorados de forma remota pelo gerenciador ABB Aurora Vision® Plant Management Platform. Tais dados foram extraídos via internet e armazenados em um banco de dados brutos.

A pesquisa de doutorado está dividida em dois artigos publicados em revista qualis A1. O Primeiro artigo apresenta o método desenvolvido para a aplicação de um algoritmo técnico-estatístico capaz de analisar uma grande amostra de microgeradores descentralizados com registros de dados de geração FV em baixa resolução temporal. O segundo artigo analisa o comportamento de uma unidade representativa da amostra de microgeradores instalados na região de Florianópolis, sob duas diferentes óticas: concessionária e consumidor.

O fluxograma do algoritmo técnico-estatístico apresentado no primeiro artigo está dividido em seis etapas:

- (i) Entrada: banco de dados brutos de geração FV;
- (ii) Filtro Técnico: nessa etapa são descartados os sistemas com ausência de aquisição de dados ou que não atendem aos quesitos técnicos adotados;
- (iii) Transformação técnica: os dados dos microgeradores selecionados pelo filtro técnico são transformados em indicadores de produtividade;
- (iv) Filtro Estatístico: nessa etapa são descartados os *outliers,* ou seja, sistemas discrepantes da amostra;
- (v) Transformação estatística: realizados os cálculos de indicadores estatísticos da amostra;
- (vi) Saída: banco de dados tratados e validados para análises de performance dos sistemas.

Dentre o grande volume de dados brutos existente na plataforma ABB Aurora Vision®, foi identificada cada unidade de microgeração cadastrada no sistema e posteriormente extraídos os valores individuais da potência FV, com resolução temporal de cinco minutos, expressos em kW. Antes da aplicação dos filtros técnicos, tais registros foram integrados e transformados em registros de energia FV, em base horária, expressos em kWh.

Para garantir a qualidade técnica dos dados medidos de cada microgerador FV, ou seja, identificar automaticamente e descartar dados com valores incorretos (oriundos de sistemas com falhas técnicas ou de sistema de comunicação de dados com defeito), foram adotadas as seguintes premissas:

- (i) Validação de dados diários de geração FV: são contabilizados os sistemas FV que apresentam número de registros horários maior ou igual a oito horas (equivalente a um dia com no mínimo oito horas de geração FV) e potência FV mínima de 50 W e validados os dados individuais registrados de geração FV para tal dia;
- (ii) Validação de dados mensais de geração FV: são contabilizados os sistemas FV que apresentam, no mínimo, 15 dias de dados diários validados pelo filtro (i);
- Validação de dados anuais de geração FV: são contabilizados os sistemas FV que apresentam registros de dados mensais de geração FV validados (pelos filtros (i) e (ii)) nos 12 meses do período analisado.

Na etapa de transformação técnica, os dados de geração FV de cada microgerador são transformados em indicadores de produtividade diária, no intervalo de tempo especificado, expressos em kWh/kWp·dia.

O Estado de Santa Catarina possui 1.000 coordenadas georreferenciadas no Atlas Brasileiro de Energia Solar. Esses pontos foram mapeados e divididos em quatro faixas de irradiação (quatro quartis estatísticos), nomeados como faixas de irradiação 1, 2, 3 e 4, com valores da média diária anual da irradiação global inclinada da amostra. Para cada faixa de irradiação solar inclinada, através da identificação da localização de cada microgerador, foram calculados os respectivos rendimentos energéticos (*Yields)* FV teóricos da amostra selecionada para aplicação dos filtros estatísticos. Convém destacar que esse filtro é aplicado sobre a amostra de microgeradores selecionados a partir da aplicação dos filtros técnicos. Para garantir a qualidade e significância dos *Yields* medidos para o conjunto de microgeradores analisado, foi aplicado o método *Interquartile Range.*

Na etapa de transformação estatística, a significância dos dados foi analisada por meio do teste de normalidade da distribuição, que adotou o método QQ-plot (R^2). Neste caso, dados de produtividade medida são correlacionados com dados de uma distribuição normal. Para correlação maior que 0,9 a amostra é caracterizada por uma distribuição normal.

A exploração e análise estratégica de dados adotadas neste trabalho segue como referência os passos da metodologia de BI. A aplicação desse processo para a análise de dados de irradiação e de geração solar FV, somada ao conhecimento da área de sistemas de energia elétrica, resultou no método *Energy Intelligence* (E-BI). Os componentes do BI são divididos em quatro principais etapas: (i) Dados operacionais e dados brutos; (ii) Processos de ETL: Extração, transformação e carga; (iii) *Data Warehouse*: armazenamento de dados já organizados e processados; (iv) Visualização de resultados: indicadores, gráficos e painéis (*dashboards).* A visualização das informações técnicas aliada ao conhecimento dá suporte à tomada de decisão por profissionais técnicos envolvidos com a operação ou administração de múltiplos sistemas FV conectados em uma malha de GD.

Para analisar o comportamento de uma unidade representativa da amostra, o segundo artigo apresenta um método dividido em cinco etapas principais:

Na primeira etapa, foi realizada a análise do recurso solar disponível em bancos de dados de satélites (Atlas Brasileiro de Energia Solar 2ª edição) e da estação meteorológica mais próxima da localização do sistema FV. Na segunda etapa, tanto a geração real de energia medida a partir do sistema FV foi comparada com a geração de energia estimada (simulações teóricas e via ferramenta computacional PVsyst®), bem como as métricas de produtividade estimadas e medidas (Produtividade anual de energia e *Performance Ratio* - PR). A terceira etapa consistiu em analisar as faturas mensais de energia elétrica da Unidade Prossumidora (UP) no período de um ano antes do projeto Bônus FV da CELESC, e um ano após o seu término, a fim de avaliar, sob a ótica da concessionária de distribuição e da UP, o desempenho energético e os impactos financeiros proporcionados pela adoção da tecnologia FV. A quarta etapa consistiu na avaliação das emissões evitadas, proporcionadas pela adoção da energia solar FV. A quinta etapa teve como objetivo realizar uma análise comparativa entre o estudo individual da UP com a média das demais residências FV situadas na região de Florianópolis.

Tanto a energia quanto os impactos financeiros, bem como os impactos ambientais proporcionados pelo Projeto Bônus PV da CELESC, vêm apenas do uso da geração de Energia Solar Fotovoltaica no domicílio, já que não houve outras mudanças implementadas.

Resultados e discussões

Embora o método desenvolvido apresente caráter geral, esta pesquisa teve como foco desenvolver uma metodologia para a avaliação da produtividade energética de um grande conjunto de microgeradores fotovoltaicos residenciais no estado de Santa Catarina. Para tanto, a exploração e análise estratégica dos dados foi feita por meio de conceitos de BI combinados com um algoritmo técnico-estatístico para avaliar a produtividade (*Yield*) FV.

Os resultados mostraram que o método desenvolvido neste trabalho garante, com eficiência e eficácia, a qualidade e significância para grandes volumes de dados operacionais de geração FV, sem utilizar trabalhosas técnicas de *Gap-filling*.

No período analisado, observou-se grande número de microgeradores FV removidos pela aplicação dos rigorosos filtros técnicos definidos. Durante os 12 meses do ano, mais da metade do conjunto de geradores FV (52,1% ou 651 unidades) apresentou pelo menos um mês com problemas nos dados de geração (normalmente, falta de registro na aquisição de dados). Das 1.250 coberturas FV idênticas analisadas, apenas 598 unidades passaram com êxito por todos os filtros técnicos. A metodologia proposta e os resultados obtidos neste estudo de caso evidenciaram claramente a falta de monitoramento adequado para identificar anormalidades nos dados de geração dos telhados FV do Programa Bônus FV.

A aplicação do filtro estatístico após a aplicação dos filtros técnicos na maioria dos grupos de amostras removeu menos de 10% dos *outliers*. Em geral, foi necessário aplicar dois ciclos do filtro estatístico até que não houvesse mais discrepância nos dados. Para avaliar o *Yield* dos microgeradores FV, restou uma amostra composta por 570 sistemas.

Para irradiação solar global inclinada anual variando entre 3,78 e 4,28 kWh/m^2·dia (Faixa 1), o *Yield* FV médio diário foi de 3,35 kWh/kWp·dia, desvio padrão de 0,17 kWh/kWp·dia e margem de erro de 0,02 kWh/kWp·dia, para 95% de confiabilidade.

Para irradiação solar global inclinada anual variando entre 4,28 e 4,48 kWh/m^2·dia (Faixa 2), o *Yield* FV médio diário foi de 3,74 kWh/kWp·dia, desvio padrão de 0,17 kWh/kWp·dia e margem de erro de 0,03 kWh/kWp·dia, para 95% de confiabilidade.

Para irradiação solar global inclinada anual variando entre 4,48 e 4,74 kWh/m^2·dia (Faixa 3), o *Yield* FV médio diário foi de 3,82 kWh/kWp·dia, desvio padrão de 0,20 kWh/kWp·dia e margem de erro de 0,03 kWh/kWp·dia, para 95% de confiabilidade.

Para irradiação solar global inclinada anual variando entre 4,74 e 4,95 kWh/m2·dia (Faixa 4), o *Yield* FV médio diário foi de 3,90 kWh/kWp·dia, desvio padrão de 0,20 kWh/kWp·dia e margem de erro de 0,04 kWh/kWp·dia, para 95% de confiabilidade.

A geração média anual de cada telhado FV analisado gira em torno de 3.353 kWh/ano (rendimento anual = 1,265 kWh/kWp·ano), o que corresponde a uma emissão evitada de CO_2 de 268,25 $kgCO_2$/ano. Para todo o conjunto de 1.250 telhados FV, a emissão média de CO_2 evitada é de cerca de 335,30 tCO_2/ano.

Os resultados foram apresentados visualmente em mapas via SIG e por meio de indicadores estatísticos, tais como, *Yield* médio diário, variabilidade dos dados, valores máximos e mínimos, margens de erro para 95% de confiabilidade, entre outros. A qualidade e significância dos dados foi garantida pelo algoritmo técnico-estatístico adotado.

A ferramenta *Energy Business Intelligence* (E-BI) facilitou o entendimento do fluxo de informações relacionadas a centenas de geradores FV e pode ser adotada para qualquer tamanho de amostra. Foi possível, através dos *dashboards* desenvolvidos, visualizar rapidamente o potencial solar FV em todo o território analisado, com base na informação do recurso solar disponível a partir de dados de satélite e a produtividade medida de cada sistema FV. Os resultados obtidos nesta pesquisa podem ser usados para prever, com 95% de confiabilidade, a geração mensal/anual de futuros sistemas FV a serem instalados em Santa Catarina, e a mesma metodologia pode ser aplicada *mutatis mutandis* para produzir resultados análogos em qualquer lugar.

A novidade desta pesquisa está no desenvolvimento de um algoritmo capaz de avaliar tecnicamente e estatisticamente uma grande amostra de sistemas FV conectados à rede elétrica. A utilização de tal algoritmo possibilita a dispensa do uso de trabalhosas técnicas de preenchimento de lacunas (*gap filling).* Adicionalmente, o método desenvolvido permitiu avaliar a produtividade energética de um grande conjunto de microgeradores fotovoltaicos residenciais instalados em telhados no Estado de Santa Catarina.

O método desenvolvido utiliza conceitos de BI para estruturar e gerenciar as informações em *dashboards* com indicadores predefinidos, permitindo a aplicação de uma ferramenta com uma linguagem já conhecida por muitos gestores para auxiliar remotamente na tomada de decisão das empresas responsáveis pela gestão de conjuntos de sistemas FV conectados à rede elétrica.

Atualmente, os pequenos produtores de energia são os principais responsáveis pela capilaridade e disseminação da GD FV no Brasil e no exterior. Esse mercado em crescimento ainda é recente e tem muito a evoluir. O conhecimento sobre gerenciamento de dados de GD FV ainda não é completamente dominado pelas concessionárias de energia elétrica, e ferramentas ou métodos como os apresentados neste trabalho são projetados para auxiliar nessa tarefa.

Foram também avaliados, sob a ótica da concessionária de distribuição e sob a ótica do prossumidor, os impactos técnico-econômicos proporcionados pela adoção da geração de energia solar FV em uma das residências unifamiliares que foi contemplada pelo programa Bônus FV da CELESC, durante um período de 12 meses (2019), avaliando a produtividade FV (geração FV) em todas as quatro estações do ano.

Para o sistema FV analisado, os resultados mostraram que o *Yield* anual medido foi superior ao *Yield* anual esperado com base nos valores de irradiação anual obtidos por imagens de satélite (1.379 kWh/kWp *versus* 1.315 kWh/kWp), com diferença de 4,8%, bem dentro da variação interanual do recurso de radiação solar (PEREIRA et al., 2017). Os resultados também mostraram que o desempenho real do sistema FV (PR medida) é menor nos meses mais quentes, pois a tecnologia FV de silício cristalino possui um elevado coeficiente de perda de potência com o aumento da temperatura de operação. A PR medida apresentou valores superiores a 80% nos meses de janeiro a setembro, atingindo um pico de 94,1% (setembro) e um valor menor de 76,3% (outubro). Os altos valores encontrados para a PR podem ser justificados por algum dos seguintes fatores: baixo carregamento do inversor (ILR = 2,65/3,00 = 88%), ocorrência de eventos significativos de sobreirradiância (*overirradiance)* (MARTINS; MANTELLI; RÜTHER, 2022; NASCIMENTO et al., 2019, 2020) na localização da instalação do sistema FV (o que aumenta sua produção de energia FV), telhado da casa ser pintado de branco, o sistema FV ser instalado em uma área de telhado alto com boa ventilação.

Do ponto de vista da concessionária de distribuição, os resultados mostraram que o consumo anual da Unidade Prossumidora (UP) antes da instalação FV (janeiro a dezembro/2017) foi de 4.780 kWh/ano. Após a instalação FV (janeiro a dezembro/2019), o consumo anual da UP foi de 3.919 kWh/ano (redução de 18% no consumo) e o excedente de energia ativa alimentada na rede elétrica (compensação nas faturas da UP) foi de 2.430 kWh/ano.

Do ponto de vista do consumidor, os resultados mostraram que o consumo anual total da UP antes da adoção do telhado FV foi de 4.780 kWh/ano e após a instalação FV foi de 5.143 kWh/ano. Após o programa Bônus FV, a UP apresentou um aumento de 7,6% (363 kWh) no consumo total anual de energia elétrica, que pode ser devido ao verão 2018-2019 ter sido mais quente do que o habitual em Florianópolis. No entanto, a **redução anual de suas despesas com a concessionária de energia foi de 54%** (US$ 398,3, em conversão janeiro/2018).

Observa-se que a agregação da geração FV proporcionou emissão anual evitada de gases de efeito estufa a serem lançados na atmosfera de aproximadamente 273 kgCO_2 por residência. No período analisado, os resultados mostram que a UP evita em média 1kg de CO_2 a cada 13,3 kWh gerado pelo sistema do Kit Bônus Fotovoltaico. Ainda que as emissões de CO_2 evitadas por unidade consumidora (UC) apresentem individualmente baixos valores, seu grande potencial de redução se encontra na utilização da energia FV em larga escala, contribuindo, assim, efetivamente, com a redução do efeito estufa e com a preservação ambiental.

Os resultados mostram a viabilidade econômica para os sistemas de telhados FV instalados, pois o VPL > 0 até o 25º ano (vida útil), para todas as taxas de juros (0% a 11,5%), em ambos os cenários, com subsídio (programa de bônus FV CELESC) e sem subsídio (Mercado). Para o parâmetro da TIR, o cenário subsidiado apresenta atratividade econômica para todas as taxas de juros, ou seja, TIR > TMA, enquanto o cenário sem subsídio apresentou um investimento economicamente atrativo para taxas de juros que variam até 5,5%. Além disso, para o sistema FV sem subsídio, a LCOE apresentou valores competitivos (variando entre 0,17 US$/kWh e 0,23 US$/kWh) em comparação com as tarifas cobradas pela concessionária, para TMA até 5,5%.

Com base nas análises estatísticas e comparativas apresentadas nos resultados, foi possível concluir que um pequeno sistema FV, utilizando módulos FV convencionais de silício multicristalino e instalados sobre telhados residenciais na cidade de Florianópolis, irá produzir uma média de 3,78 kWh/kWp·dia ou 1.379 kWh/kWp·ano, para uma irradiação horizontal global anual de 1.500 kWh/m²·ano no local.

O crescimento maciço de pequenos produtores conectados à rede de distribuição de eletricidade é uma nova realidade e gera um novo paradigma com o que as concessionárias devem lidar. Nesse contexto, os resultados mostraram que é de **extrema importância para as concessionárias começarem a coletar dados operacionais sobre sistemas FV conectados à rede que permeiam cada vez mais suas redes de distribuição.**

Por fim, foi concluído que o principal papel das UPs é reduzir as despesas com energia elétrica para os consumidores, bem como contribuir para a GD de forma descentralizada e sustentável. Com a chegada da regulamentação para GD, a tecnologia FV se tornou mais acessível aos pequenos consumidores residenciais, que hoje são os principais usuários dessa fonte no Brasil e no mundo.

Considerações finais

A pesquisa de doutorado apresentou um método para avaliar o comportamento da produtividade de múltiplos sistemas de micro GD-FV. Esse método foi desenvolvido: (i) devido à necessidade de garantir a qualidade e significância de um grande volume de dados operacionais de geração FV, e (ii) devido a lacunas existentes quanto ao tratamento e à gestão de dados no gigante mercado de GD-FV. Foi possível, por meio de um estudo de caso, explorar dados de geração solar FV de uma forma exclusiva que ainda poucos profissionais ou cientistas têm acesso no Brasil.

O maior desafio encontrado em análises exploratórias de dados é a garantia da qualidade dos dados e, para resolver esse desafio, o algoritmo técnico-estatístico oferece, com eficiência e eficácia, a segurança e qualidade de um grande volume de dados a ser analisado.

Sistemas FV residenciais vêm se tornando cada vez mais populares no mundo, mas o perfil desse tipo de consumidor que é também produtor (prossumidor) ainda é pouco explorado pelas distribuidoras ou grupos de pesquisa, em parte devido à falta de ferramentas de apoio à gestão da informação com indicadores fundamentados e relevantes para auxílio à tomada de decisão ou previsões de produtividade. As conclusões respaldam a validade da replicação do~~s~~ método~~s~~ apresentado~~s~~ para a região sul do Brasil, em outras regiões brasileiras e do mundo.

Atualmente, por mais que a tecnologia solar FV esteja dentro de um cenário de crescimento exponencial e popularizada para o público em geral, ainda existem dúvidas sobre os papéis e os benefícios da energia solar em telhados, bem como o entendimento dos diferentes pontos de vista dos agentes (concessionária e consumidor) em relação à gestão do fluxo de consumo e de geração de energia elétrica, bem como o acúmulo e compensação de créditos excedentes e que não foram consumidos de forma instantânea pela UP. Portanto, espera-se contribuir aos esforços internacionais e, principalmente para o crescente mercado brasileiro, na disseminação do conhecimento e na popularização da energia solar aplicada a edificações, bem como conscientizar usuários sobre o uso correto da tecnologia, visando uma maior eficiência energética.

SUMMARY

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ACRONYMS

BAPV - Building-Applied Photovoltaic Systems

BI - Business Intelligence

BIPV - Building-Integrated Photovoltaic Systems

CU – Consumer Unit

DG - Distributed Generation

E-BI - Energy Business Intelligence

EECS - Energy Compensation System

GHI - Global Horizontal Solar Irradiation

GIS - Geographic Information Systems

GPOA - GHI to plane-of-array

GTI - Global Latitude-tilted solar irradiation

IRR - Internal Rate of Return

LCOE - Levelized Cost of Energy

MARR - Minimum Attractive Rate of Return

NPV - Net Present Value

PR - Performance Ratio

p-Si - Multicrystalline Silicon

PU - Prosumer Unit

PV – Photovoltaic

ZEB - Zero Energy Building

1 INTRODUCTION

The generation of electricity from renewable sources (mainly solar) and the smart management of the transmission, distribution, and consumption of electricity have undergone major technological advances that have been widespread especially in the last decade, notably due to the urgency in reducing the Emission of Greenhouse Gases (EGG) to stop the increasingly frequent and increasingly intense climate catastrophes resulting from global warming.

Unless global EGG are cut nearly in half by 2030, extreme weather impacts are likely to be felt worldwide, according to the latest report from the Intergovernmental Panel on Climate Change (IPCC), released on April 4, 2022: "Climate Change 2022: Mitigation of Climate Change" (IPCC, 2022). According to this report, if urgent actions are not taken, humanity will fail to restrict warming to 1.5°C, the threshold that moves us away from a future with more fires, droughts, storms, and more extreme weather events. At current levels of growth, however, greenhouse gas emissions will likely result in twice as much warming: approximately 3.2°C by 2,100.

Buildings are responsible for most of the energy consumption in Brazil (EPE, 2021) and worldwide (IEA, 2021). In Brazil, the residential sector was responsible for 31% of the total electricity consumed in 2020, second only to the industrial sector (EPE, 2021).

As for PV-DG systems in Brazil, 78% of them are installed in Consumer Units (CUs) of the residential sector, and this represents 45% of the cumulative PV-DG power installed in the country. (ANEEL, 2022). With this, it is noted that the residential sector has much to contribute to boost this reduction in emissions, using more efficient and smarter electrical devices, the integration of photovoltaic (PV) generators and storage systems, directly impacting the generation, transmission, and distribution of electricity.

Within the set of PV-DG systems installed in the residential sector, **90%** of them have at most 10 kWp of nominal power. These systems account for **67%** of the cumulative residential installed PV-DG power and totalize nearly **700,000** systems (ANEEL, 2022), and are expected to double in 2022 (ABSOLAR, 2022a). Due to their high dispersion, the development of appropriate data management platforms and methodologies is essential.

Although the PV market has been showing a large annual growth in Brazil since 2012, PV generation still represents only 7.6% (ABSOLAR, 2022b) of the national electricity generation mix. This low PV participation in the national mix occurs due to technical, economic, social, managerial, and political reasons. Among the main barriers identified are issues around the quality of PV systems installation, the high cost of the initial investment, the dependence on financing for the acquisition of PV systems, the lack of knowledge of PV technology by a large portion of consumers, the after-sales services, the dependence on imports of PV modules from China, the economic and legal framework, and the public policies to encourage PV-DG.

Given this promising market scenario, but with so many issues to deal with, the analysis of the volume of data from thousands of new microgenerators has been an arduous task, since it is common for several microgenerators to present faulty data caused by many different facts and that lack the use of reliable methods for the detection and diagnosis of faults in PV systems. This fact makes necessary the development of mechanisms for the treatment of operational data from grid-connected PV systems, since remotely monitoring PV energy production through sensors is not a trivial task and the acquisition of this data must go through a minimally qualified technical curator. Currently there is a lack of scientific publications that simultaneously address technical and statistical methods for the analysis and processing of data from large-scale PV microgenerators.

With the advance of information technology, as well as the increased capacity to collect and store data, organizations have been seeking improvements in processing, visualizing, and interpreting the large volume of information made available daily. The speed and variety of data collection and storage is increasing fast, through both internal and external resources. This demand has led executives to adopt Business Intelligence (BI) tools for critical analysis and management of their business in a more effective way. BI is widely used in data analysis research and decision support systems.

The importance of BI depends on the types of data extracted and how they are used. The main factor, however, is the method of transforming raw data into valuable information, not the quantity of data. Therefore, defining and validating indicators becomes essential to identify the focus and the data that will be collected.

An adequate methodology to evaluate multiple generation points is essential to provide relevant information about the yield of PV generation along the areas where these systems have been installed and thus enable smarter and more appropriate management of smart grids.

A single PV microgenerator already generates large volumes of raw operational data, even at scales with low temporal resolution. For the analysis of data from the distributed grid of hundreds of PV microgenerators, its organization and storage become necessary. In this context, major challenges arise. Among them, the integration and transformation of raw data into relevant information for control, management, and the decision-making process.

The exploration and strategic analysis of data - through the implementation of BI concepts, combined with an algorithm based on technical-statistical methods - can provide managers with relevant information about the performance of the PV systems that generate this data and, thus, support decision making quickly and easily.

In the years 2017 and 2018, within the scope of the Photovoltaic Bonus program of the local distribution utility CELESC (CELESC, 2017), 1250 identical residential rooftop PV generators were installed and connected to the low voltage power grid. Each of these dispersed PV systems is rated at 2.65 kWp, distributed throughout the state of Santa Catarina - Brazil, with a total installed capacity of approximately 3 MWp. This work aims to analyze, for the period between January and December 2019, the monthly and annual PV yield of multiple distributed microgeneration systems, using novel BI applications, entitled Energy Business Intelligence (E-BI), combined with a technical-statistical algorithm to evaluate the yield of such systems. The results are presented visually on maps via Geographic Information Systems (GIS).

From the consumer's perspective, distributed microgeneration represents savings in electricity costs. With this, a new agent was born in the electric scenario, the **prosumer** (producer + consumer), interested in investing in self-generation. The literature lacks in-depth analysis and methods to assess the role and benefits of this new agent (prosumer) in the context of DG. Therefore, this work aims to evaluate, from the utility's perspective and the prosumer's perspective, the technical-economic impacts provided by the adoption of PV generation. To this end, a case study was developed in a residence contemplated by the "Photovoltaic Bonus" project with a methodology to evaluate, under these different perspectives, the impacts of the adoption of solar PV generation in residences in the context of the regulation of the Brazilian electricity market.

In the following subtopics will be developed issues and concepts related to the PV-DG market in Brazil, the regulatory aspects for DG in Brazil, solar irradiation database (among them the Brazilian Atlas of Solar Energy), concepts related to the PV technology (Yield and PR), computational tools, and information about this doctoral thesis, such as: problem and relevance, contribution and innovation, objectives. As a last subtopic, the structure of this thesis is presented.

1.1 Contextualization

This doctoral thesis was developed in article format and based on the recommendations of Resolution 03/PPGEC/2020. Therefore, the literature review is incorporated into the published and internationally reviewed articles. Despite this, the content covered in this research is supplemented and contextualized by updating the following subjects:

- Regulatory aspects for DG in Brazil
- PV-DG market in Brazil
- Solar irradiation databases
- Brazilian Solar Energy Atlas
- Productivity (Yield)
- Performance Ratio (PR)
- Computational tools

1.1.1 Regulatory aspects for DG in Brazil

In Brazil, the regulatory aspects for DG are partially adequate to support the growth of the PV market. Periodic revisions in legislation are positive and tend to adapt mainly to the residential market (DE DOYLE et al., 2021), with the aim of providing more freedom and flexibility for the consumer to effectively become a **prosumer** (consumer + producer).

In April 2012, the National Electric Energy Agency (ANEEL) approved the Normative Resolution (NR) 482/2012 (ANEEL, 2012), which establishes rules for distributed micro- and minigeneration through renewable energy sources – solar (photovoltaic), hydro, biomass and wind – and for qualified cogeneration. For microgeneration, the limitation initially was up to 100 kW of power with connection at low voltage, and, for minigeneration, the installed power was above 100 kW up to a maximum of 1 MW with connection at medium voltage.

Since NR 482/2012 came into effect, Brazilian consumers can participate in an Electric Energy Compensation System (EECS), through which it is possible to generate energy for their own consumption directly in the building and store the surplus in the public grid, through credits, for later use. The active energy injected into the grid is later compensated with the active energy consumption of the same consumer unit (CU) or of another unit with the same ownership. This credit in quantity of active energy (kWh) should be consumed within a maximum period of 36 months.

In November 2015, there was an update in the NR 482/2012, through NR 687/2015 (ANEEL, 2015), and the consumer now has 60 months to use the energy credits. In addition, microgenerators are now characterized with installed power less than or equal to 75 kW, and distributed minigeneration is now applied to systems with power greater than 75 kW with a limit of up to 5 MW.

The review of NR 482/2012, through NR 687/2015, besides allowing remote self-consumption, introduced concepts about community systems of distributed micro and minigeneration. These were: “Shared Generation” and “Enterprises with Multiple Consumer Units” (EMCUs). The new concepts of NR 687/2015, incorporated into the text of NR 482/2012, refer to the sharing of energy credits between associated CUs in consortium or cooperative, and condominium, in the case of EMCUs. Remote self-consumption, on the other hand, applies to the sharing of credits resulting from surplus power generation injected into the electric grid, between CUs belonging to the same owner. Remote DG is characterized by the generation of energy in a CU, but compensated in another CU.

Shared generation is characterized by the gathering of consumers and producers, within the same concession or permission area, by means of a consortium or cooperative, composed of an individual or legal entity, that has a prosumer unit (producer + consumer) with distributed micro- or minigeneration in a different location from the CUs in which the surplus energy will be compensated.

The modality of generation by condominiums can be applied to residential or commercial condominiums. All the CUs must be located on the same property, or must be neighboring, if they are not crossed by public roads.

The consortium generation modality is characterized by the gathering of companies that make an agreement among themselves through a business contract, in order to obtain benefits from the sharing of a DG system. The consortium must incorporate a CNPJ, through a specific purpose company and own the CU where the DG system will be installed.

The cooperative modality is characterized by the union of individuals with a common goal, who wish to come together voluntarily to generate their own energy through a DG system. The energy generated by the DG system is compensated in the CUs of the cooperative members. According to the Organization of Brazilian Cooperatives (OBC), the minimum group to form a cooperative is 20 people. Exceptionally, according to Law 5.764/71, legal entities with the same objectives and economic values as individual members, may also be admitted to the cooperative, provided that the minimum of 20 individuals (individuals) has been reached (BRASIL, 1971; LIMA, 2018).

Sharing economy models such as the solar cooperative format are a very recent reality in the country, which results in the emergence of some barriers during the process of popularizing the business. Knowledge and understanding on the part of potential users of the technology is very low.

The need to pay the contracted demand for PV systems above 75 kWp is still considered a barrier to the use of this technology in Brazil. In this context, all Brazilian solar cooperatives so far are registered as microgeneration with nominal power limited to up to 75 kWp. However, market agents and associations such as the Brazilian Solar Energy Association (ABSOLAR, 2022b) have been expressing this concern as a major barrier to the development of minigeneration cooperatives (from 75 kWp up to 5 MWp).

In April 2015, the National Council of Finance Policy (CONFAZ) published ICMS agreement 16/2015 (CONFAZ, 2015), which allows states and the Federal District to exempt ICMS taxes from net metering operations for DG. However, ICMS exemptions are only possible for DG projects up to 1 MW (as the agreement is prior to the extension of minigeneration size to 5 MW allowed by NR 687/2015) and are not possible for shared DG modalities (as the agreement is prior to the inclusion of shared DG allowed by NR 687/2015).

Law 14.300/22, sanctioned on January 6, 2022, established the Legal Landmark of Distributed Microgeneration and Minigeneration. The law regulates the modalities of generation, the EECS, and the Social Renewable Energy Program (SREP). This law had great support from companies operating in the DG sector, as it provides legal security for activities that were previously regulated by ANEEL's normative resolutions.

1.1.2 PV-DG market in Brazil

The growth of DG in Brazil is related to: (i) the decentralization of the electricity market; (ii) the diversification of the electric matrix; (iii) the expansion of the electric energy supply and the Gross Domestic Produc (GDP) growth; (iv) the reliability of the electric energy supply, especially in times of water scarcity (MAESTRI; ANDRADE, 2022).

With NR 482/2012, DG began to be introduced into the Brazilian electricity system in a less bureaucratic way and with the possibility of using the energy credits injected into the grid not only in the month of injection, but also in the following months, in addition to facilitating the whole process of registration and authorization of the DG system for operation and connection.

Figure 1.1 shows the evolution of the growth of solar photovoltaic installed power in Brazil, in a centralized and distributed way, per year, until April 2022. It is noted that PV-DG is responsible for most of the annual growth.

On ANEEL's Microsoft Power BI platform for DG (ANEEL, 2022), accessed on May 1st 2022, it was verified that the total accumulated PV-DG power in Brazil already reached **10 GWp**[1]. Figure 1.2 shows the growth of PV-DG in Brazil, which has taken off recently and is expected to double during 2022.

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[1] On May 1st 2022, the date of access to ANEEL's Microsoft Power BI DG platform (ANEEL, 2022), only systems connected up to April 5th 2022 were posted in this database. That is, the actual value of the accumulated PV-DG power was already more than **10 GWp** on May 1st 2022, because the PV-DG systems installed in the period April 5th to May 1st 2022 were not yet posted. When accessing this platform again on May 3rd 2022, the total accumulated PV-DG power was already **10.34 GWp**. On this last date, information on PV-DG systems connected up to May 1st 2022 was already available on the platform.

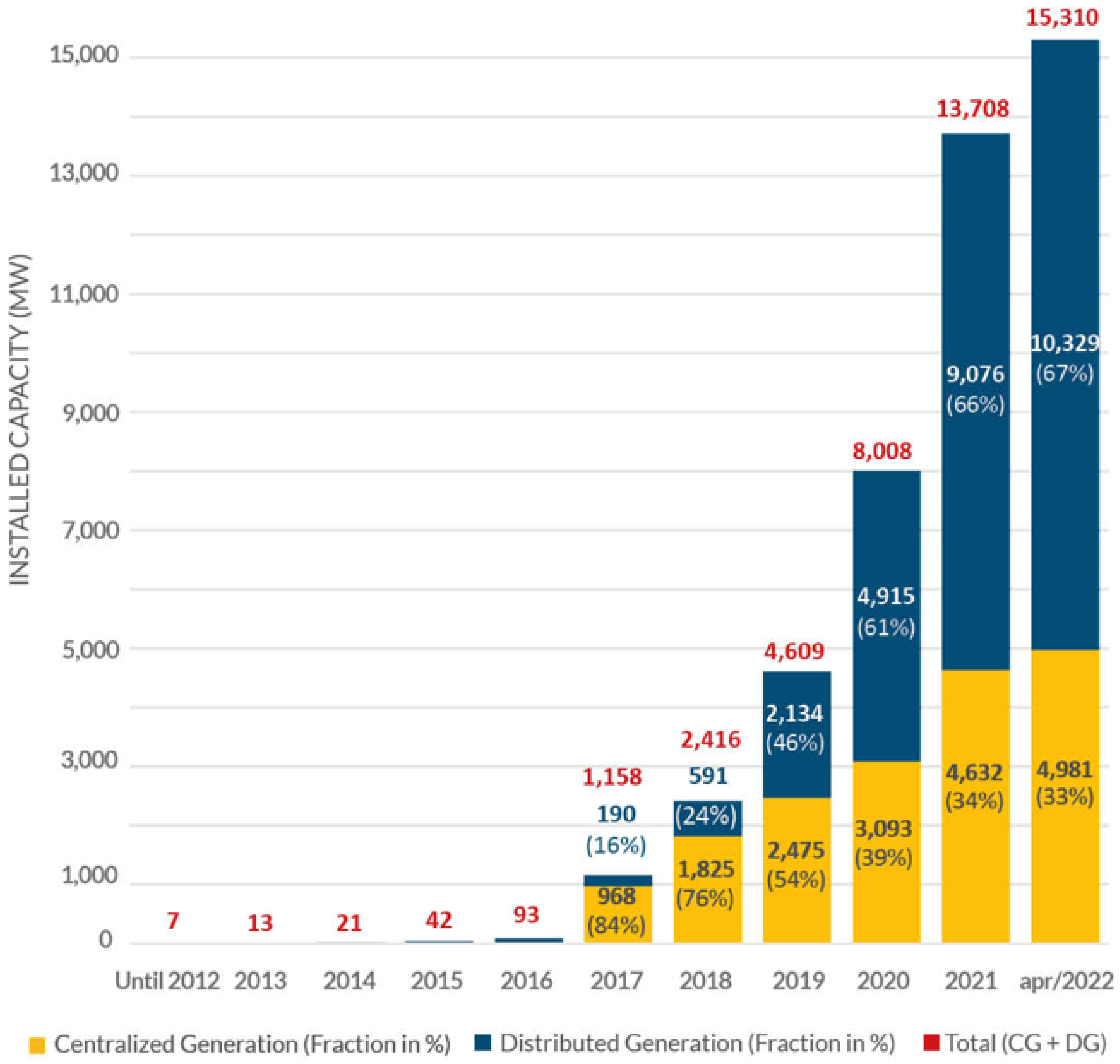


Figure 1.1. PV-DG: Installed power, per year, of connected PV systems in Brazil until April 2022. (ABSOLAR, 2022b)

The DG system registered on ANEEL's Microsoft Power BI DG platform (ANEEL, 2022), with the oldest connection date, was connected to the grid on 12/13/2008, and has the following characteristics: PV system with 25 kWp of power, installed in Bocaiúva - MG, commercial CU B3, remote self-consumption and two CUs registered to use the energy generated. There are PV-DG systems connected to the grid before 2008, and in continuous operation until today, but not yet registered with ANEEL - or at least not included in the ANEEL's Microsoft Power BI DG platform, such as the 2 kWp system installed in Florianópolis-SC, on the roof of the Mechanical Engineering Department at UFSC, which was connected to the public electric grid in **Sep/1997**. This system is the first PV system integrated to the architecture of a building in Brazil, connected to the electrical grid (RÜTHER; VIANA; SALAMONI, 2010). Before this, a few PV-DG systems were connected to the grid of a building, but they were systems in structures not integrated to the building.

Before the regulation given by NR 482/2012 (ANEEL, 2012), it was possible to obtain exceptional authorization from utilities to connect a DG system to the public power grid - as is the case for the two PV systems mentioned in the previous paragraph and the other systems installed before this normative resolution came into effect, but it was not possible for energy credits to be offset in subsequent months. It was only allowed to reduce consumption in the same month.

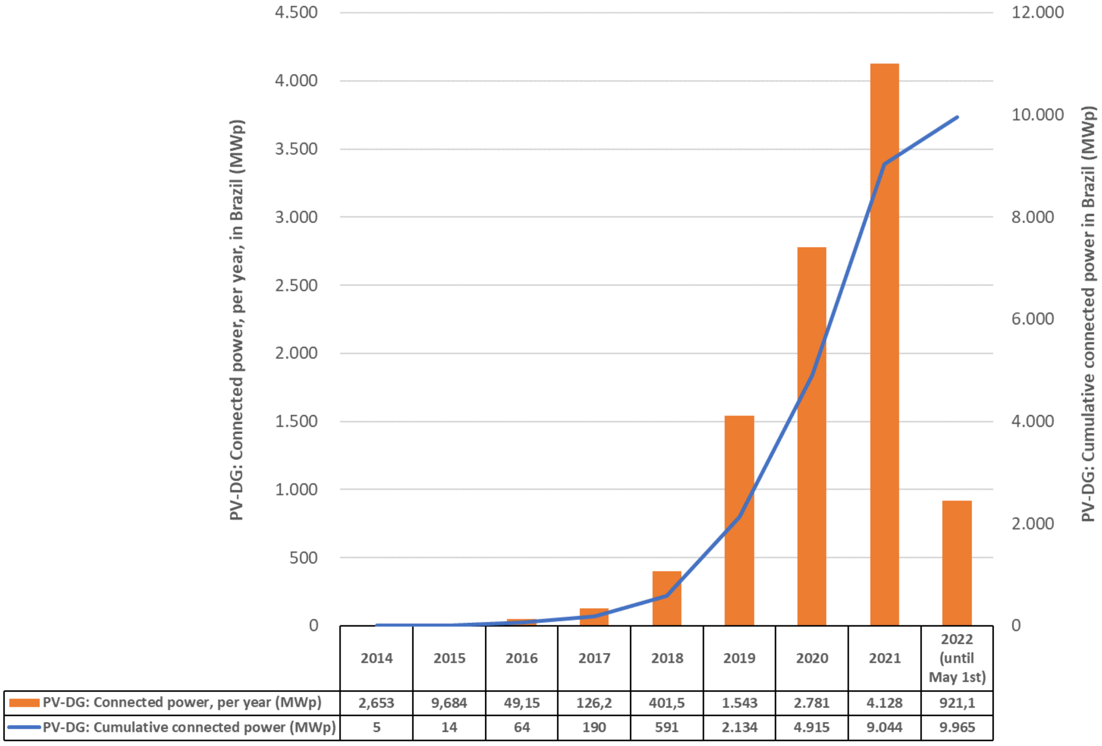
Table 1.1 shows the annual totals of the PV-DG market in Brazil, since the oldest grid connection date registered with ANEEL (2008), as well as the annual growth of the PV-DG market in Brazil. From 2011 to 2019 the total PV-DG power values had exponential growth. But even from 2019 to 2021, this growth remained quite high: above 80% per year. The yellow highlights show the exponential growth each two years in PV-DG connected power.

Table 1.1. PV-DG: Annual variation in the number of connected PV systems and consumer units that receive energy credits in Brazil, as well as the connected PV power. Source: Generated from (ANEEL, 2022). Access: May 1st 2022.

Year	**PV-DG: Number of connected systems**	**PV-DG: Number of consumer units that have started receiving credits**	**PV-DG: Connected power (MWp)**	**PV-DG: Increase in the total number of connected systems in the year, compared to the total of the previous year**	**PV-DG: Increase in the total number of consumer units that began to receive energy credits in the year, compared to the total of the previous year**	**PV-DG: Increase in the total power of connected systems in the year, compared to the total of the previous year**
2007	-	-	-			
2008	1	2	0.025			
2009	2	2	0.023			
2010	6	7	0.040			
2011	7	11	0.101			
2012	6	7	0.467			
2013	51	64	1.473	750%	814%	215%
2014	294	321	2.653	476%	402%	80%
2015	1,428	1,651	9.684	386%	414%	265%
2016	6,676	7,602	49.15	368%	360%	408%
2017	13,881	16,609	126.2	108%	118%	157%
2018	35,958	46,586	401.5	159%	180%	218%
2019	123,984	158,365	1,543	245%	240%	284%
2020	224,020	285,268	2,781	81%	80%	80%
2021	420,699	527,971	4,128	88%	85%	48%
2022 (until May 1st)	100,000	125,165	921.1			
TOTAL	**927,013**	**1,169,631**	**9,965**			

Figure 1.2 presents the evolution of the installed PV power (per year and cumulative) of connected PV-DG systems in Brazil until May 1st 2022 (ANEEL, 2022). In this figure you can better visualize how significant the

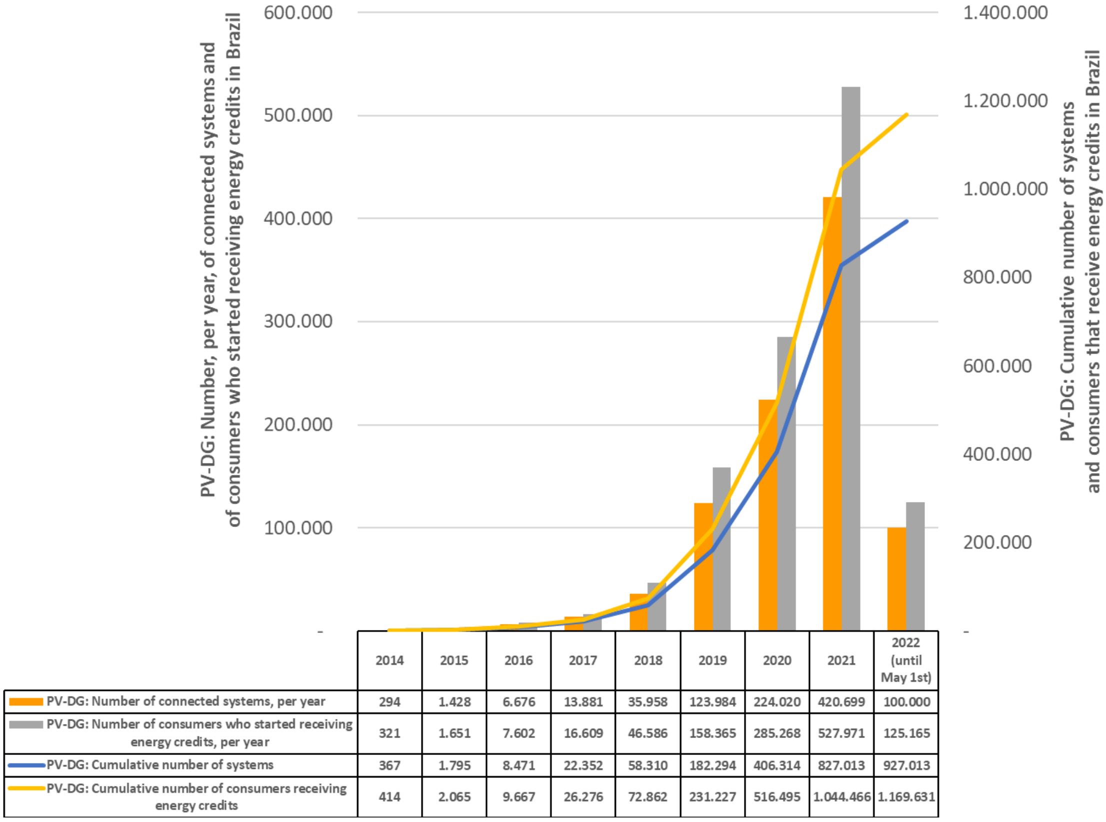
annual growth of this market in the country is. In Figure 1.3 it is also possible to see the annual growth of this market, but this time relative to the increase in the number of PV-DG systems and the number of CUs that use the energy generated by these systems.



	2014	2015	2016	2017	2018	2019	2020	2021	2022 (until May 1st)
▬ PV-DG: Connected power, per year (MWp)	2,653	9,684	49,15	126,2	401,5	1.543	2.781	4.128	921,1
― PV-DG: Cumulative connected power (MWp)	5	14	64	190	591	2.134	4.915	9.044	9.965

Figure 1.2. PV-DG: Installed power (per year and accumulated) of connected PV systems in Brazil until May 1st, 2022.

Source: Generated from (ANEEL, 2022). Access: May 1st 2022.



	2014	2015	2016	2017	2018	2019	2020	2021	2022 (until May 1st)
🟧 PV-DG: Number of connected systems, per year	294	1.428	6.676	13.881	35.958	123.984	224.020	420.699	100.000
▨ PV-DG: Number of consumers who started receiving energy credits, per year	321	1.651	7.602	16.609	46.586	158.365	285.268	527.971	125.165
— PV-DG: Cumulative number of systems	367	1.795	8.471	22.352	58.310	182.294	406.314	827.013	927.013
— PV-DG: Cumulative number of consumers receiving energy credits	414	2.065	9.667	26.276	72.862	231.227	516.495	1.044.466	1.169.631

Figure 1.3. PV-DG: Number (per year and accumulated) of connected PV systems and consumer units that started to receive energy credits in Brazil until May 1st, 2022. Source: Generated from (ANEEL, 2022). Access: May 1st 2022.

Figure 1.4 shows the dissemination of PV-DG systems throughout the national territory, with information on the cumulative PV-DG installed power per federative unit. The ranking is led by Minas Gerais (MG), São Paulo (SP) and Rio Grande do Sul (RS).

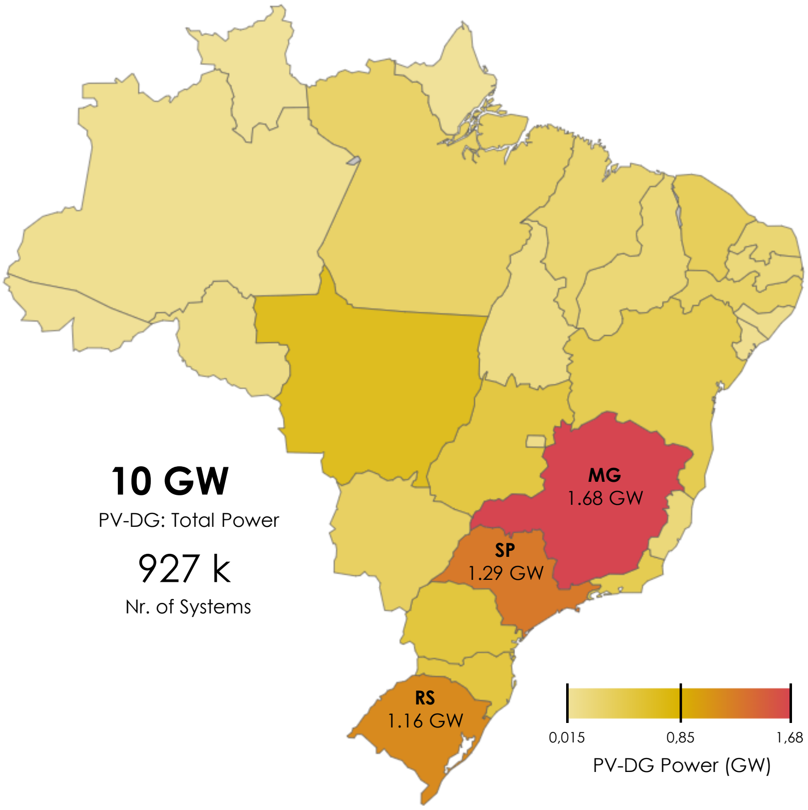


Figure 1.4. PV-DG: Accumulated installed power in each federative unit of Brazil until April 2022. Source: Generated from (ANEEL, 2022). Access: May 1st 2022.

DG has been the focus of studies and discussion in several countries, mainly due to a common concern with the future of energy generation in the world (ANTONIOLLI et al., 2018; FUNKHOUSER et al., 2015; ZHANG, 2016).

The concept of DG comes from the possibility of generating electricity near or close to the point of consumption connected to the distribution grid (ANEEL, 2012, 2015). In DG, the figure of the prosumer investor is of fundamental importance. And, among these investors, those from the residential sector are the ones that have been most relevant to the growth of the PV-DG market in Brazil.

In the process of expanding the electricity system, DG has been an option for the integration and connection of different sources along the distribution grids. When compared to the conventional way (generation, transmission and distribution), DG becomes attractive because it requires low investments, has reduced environmental impact, enables innovation and application of new technologies such as grid-connected electric vehicles and smart grids (DANTAS et al., 2017). Other advantages are flexibility of implementation, reduction of the need for new transmission lines and the reliability of the electrical system (PEREIRA JUNIOR, 2011).

The new DG model does not replace the current models already consolidated in Brazil; it coexists, integrates and the result is more reliable, adequate and efficient systems (GAMA et al., 2003).

In reviewing progress in the implementation of DG in other countries (BARUAH; ENWEREMADU, 2019; CERVONE et al., 2015; ENONGENE et al., 2019; MICHAELS; PARAG, 2016; PANG; HE; CAI, 2019; RATHORE; CHAUHAN; SINGH, 2019; RICHTER, 2013), it can be noted that the barriers found are quite similar to those that existing in Brazil (DE FARIA; TRIGOSO; CAVALCANTI, 2017; GAMA et al., 2003; GARLET et al., 2019; GUCCIARDI GARCEZ, 2017; LACCHINI; RÜTHER, 2015; SOCCOL et al., 2016), differing only by particularities related to the situations of each country (CERVONE et al., 2015).

1.1.3 Solar irradiation databases

In the sizing of PV systems, it is of fundamental importance to use solar irradiation values for the location where the system will be implemented, considering long-term periods. As there is usually no measured data *in loco*, these values are estimated from databases.

Egler (2013) evaluated the northwestern region of the American continent and analyzed the irradiation indices referring to five databases (Meteonorm 6.1, NASA SSE, 3 TIER, INPE, and NREL CSR). For Panama and Colombia, a standard deviation of ±6.1% and ±7.9%, respectively, was found. For Venezuela it was ±6.4%, Ecuador ± 13.3% and Peru ± 9.0%. Within the 38 sites analyzed, the lowest level of deviation was in Piura, Peru (± 3.1%) and the highest level was in El Puyo, Ecuador (± 14.6%). The study evaluated the long-term average of the global horizontal irradiation of the databases used for simulation of annual average generation of PV systems and showed the differences that exist between these references.

In Brazil, Antoniolli (2015) evaluated the performance of a sample of ten grid-connected PV systems in the short term (2012-2013), distributed across seven Brazilian states (SC, PR, SP, RJ, MG, BA and PA), submitted to different solar irradiation indices, comparing the real performance with that estimated by computer simulation, as a function of solar irradiation values from five existing databases (UNDP's SWERA, Meteonorm, NASA, Roriz and OLADE). Two important conclusions were presented: (i) the monthly differences between irradiation values derived from databases and measured values were more expressive than the inter-annual variability, that is, the shorter the time analyzed, the greater the absolute value of the difference between databases, and the longer the time analyzed, the smaller the absolute difference between databases; (ii) Meteonorm and NASA databases presented the smallest differences when compared to measured values (with averages below 10%).

Nascimento (2013) shows the long-term behavior (15 years) of a grid-connected PV system in Florianópolis - SC. In this study, the irradiation data measured by pyranometers, and the generation data measured through the inverter were observed, thus making it possible to evaluate the performance ratio (PR) of the system over the operation time. During the analysis the measured irradiation values were compared with values presented in the Brazilian Solar Energy Atlas (Pereira et al., 2006), and it was concluded that the Atlas values overestimate the annual irradiation by about 10% for Florianópolis.

1.1.4 Brazilian Solar Energy Atlas

The Solar and Wind Energy Resource Assessment (SWERA) project brings together, on its website, databases and analysis tools for solar and wind resources developed in collaboration with several international organizations (SWERA, 2018). The activities in Brazil and Latin America were coordinated by the Center for Weather Forecasting and Climate Studies of the National Institute for Space Research (CPTEC/INPE), which, in collaboration with UFSC, installed and operated the solar radiation measurement stations that validated the mathematical model. INPE published, as one of the results of the SWERA project, the "Brazilian Solar Energy Atlas" (PEREIRA et al., 2006). The project has information from the whole Brazilian territory with a spatial resolution of 10 km x 10 km and can be accessed at:

http://en.openei.org/wiki/Solar_and_Wind_Energy_Resource_Assessment_(SWERA).

After more than 10 years since its first edition, INPE's Center for Terrestrial System Science, through the Laboratory for Modeling and Studies of Renewable Energy Resources (LABREN), has published the second edition, expanded and revised, of the Brazilian Atlas of Solar Energy (PEREIRA et al., 2017). This is an example of cooperative work between INPE and researchers from several institutions in Brazil: the Federal University of São Paulo (UNIFESP), the Federal University of Santa Catarina (UFSC), the Federal Technological University of Paraná (UTFPR), and the Federal Institute of Santa Catarina (IFSC).

For this new edition (PEREIRA et al., 2017), over 17 years of satellite data were used and several advances in the parameterizations of the BRASIL-SR radiative transfer model were implemented, aiming to further improve the reliability and accuracy of the database produced and made available for public access. In addition to these advances, the new version contains analyses on confidence levels, on the spatial and temporal variability of the solar resource, and presents scenarios for the use of various solar technologies. Although the focus of the Atlas is on energy area, the data presented also serves users in several other areas of knowledge, such as meteorology, climatology, agriculture, hydrology, and architecture. This version of the Atlas can be accessed at: http://labren.ccst.inpe.br/atlas_2017.html.

For the development of simulations of PV generation and yield, this doctoral thesis will make use of data made available by LABREN, which are in shapefile (shp) format, in the spatial resolution of 0.1° x 0.1°

(approximately 10 x 10 km), presented through the geographic coordinate system SIRGAS[2] 2000. The data can be accessed through the same link as the digital version of the Brazilian Solar Energy Atlas.

1.1.5 Productivity (Yield)

The PV energy Yield is a simple relationship between energy generated and the installed power of a system, through which it can be determined how much each unit of nominal installed power of the PV-DG system is generating in each period. The unit typically used is the kWh/kWp·year.

In previous studies (ANTONIOLLI, 2015; ANTONIOLLI et al., 2014, 2016), this terminology has already been used to compare the yield between PV systems with different installed power, because in this way it is possible to have the same information for each system on the same scale and unit of measurement, regardless of the size or location of the systems being evaluated.

Antoniolli (2016) concluded that, for the BAPV[3] systems analyzed, oriented to the north (azimuth zero), despite presenting different values of inclination (15-45°), the differences in relation to the ideal inclination (local latitude) are not so relevant as to interfere in the PV yield or economic results. On the other hand, BAPV systems oriented to east and west (azimuthal deviation ± 90°), present a significant reduction in the yield of the system.

Simulations in the Global Solar Atlas - GSA (2018) show that systems with zero azimuth and inclinations ranging from 0-30° show insignificant (1%) difference in yield. Whereas for systems with azimuthal deviation ± 90° the differences are ≥ 10%.

1.1.6 Performance Ratio (PR)

The Performance Ratio (PR) is one of the most important variables when evaluating the efficiency of a PV system. In this analysis the quality factor for the system can be found. In this work, the acronym PR will be used to designate this variable. The PR is indicated in percentage (%) and presents the relation between the real and theoretical maximum possible energy outputs of the PV system, showing the percentage of energy available to inject into the grid after deducting energy losses (thermal losses, conduction, and inverters) and energy consumption for operation.

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[2] SIRGAS (Sistema de Referência Geocêntrico para as Américas) is a geodetic reference system resulting from the data survey performed by a network of high-precision GNSS (Global Navigation Satellite Systems) stations distributed across the continent.

[3] BAPV – *Building Applied Photovoltaics.* Photovoltaic systems applied to buildings (e.g.: on roofs and facades)

In a PV system there are losses related to the operating temperature of the PV modules, in the electrical cabling, in the DC/AC conversion in the inverter, by shading, by optimization of the electrical arrangement, among others...

As closer to 100% the PR value is, the lower the losses in the PV system are. However, it is not possible to achieve PR of 100% in practice, as there are inevitable losses that arise during the operation of a PV system. For the current technical reality, normally a well designed and installed PV system, using good quality PV modules and inverters, and which is in perfect working condition has a PR of about 80% (MARION et al., 2005; MONDOL et al., 2006; NOBRE et al., 2009; REICH et al., 2012; RÜTHER; VIANA; SALAMONI, 2010).

According to a study conducted in Germany by Reich et al., (2012) in which PR of about 100 PV systems was analyzed, an average PR value of 84% was found. Among the systems analyzed, those with the highest PR value were well installed systems with more advanced technologies. It is believed that with the advancement of studies, technical training, and the advances in technologies in the PV area, PR > 90% can become a reality (REICH et al., 2012).

1.1.7 Computational tools

Computer programs are already present in all areas, facilitating the development of many projects. In the case of PV systems, the programs improve the design by providing climatic conditions, component characteristics, and the energy demand profile.

Currently there are already programs developed by companies or universities capable of simulating PV systems (pure or hybrid) or DG-PV. There are two widely used software programs that were adopted in the current work.

- **Radiasol:** It is a software developed by the Federal University of Rio Grande do Sul (UFRGS). It uses mathematical models and in the program the calculations are performed through routines that determine the tilt effect of the face where the modules will be oriented, counting with the different irradiance components, direct and diffuse. It is also possible to change the azimuthal deviation and inclination. The user can select the diffuse radiation distribution model to perform the calculations, obtaining a set of data in the form of tables or graphs (www.solar.ufrgs.br).
- **PVSyst:** While Radiasol is used to obtain radiation values, PVSyst is a software used for sizing PV systems. It allows simulations in the final design phase or in a post-construction phase with monitoring through data sent by the PV system. The simulations can be done both for stand-alone systems and grid-connected systems (www.pvsyst.com). Using meteorological data, the program optimizes the systems, allowing the choice of a correct orientation and positioning of the PV modules in an area of maximum sun exposure and minimum shading.

The tools studied for data organization, treatment and processing were Microsoft Excel[4], Docker[5], Python[6] and Visual Studio Code[7].

The Business Intelligence (BI) tool under study is Power BI[8], a business analysis service provided by Microsoft, which provides interactive visualizations with self-service BI capabilities where end users can create reports and dashboards by themselves without having to depend on information technology staff or database administrators.

The literature review carried out during the maturation and development process of this doctoral thesis presented several BI applications in academic research, which are mostly concentrated in the areas of management, production, knowledge management, and information technology.

With the advance of information technology, as well as the capacity to collect and store data, organizations have been seeking improvements in the processing, visualization, and interpretation of the large volume of information that is made available daily. The velocity and variety of data is increasing quickly through both internal and external resources. This demand is making senior executives adopt business intelligence (BI) tools to critically analyze and manage their business more effectively (HAWKING; SELLITTO, 2015; LUFTMAN, 2010). In addition, the BI theme is frequently used in research that studies data analysis and decision support systems (FARZANEH et al., 2018; IŞIK; JONES; SIDOROVA, 2013; LARSON; CHANG, 2016; RAMAKRISHNAN; JONES; SIDOROVA, 2012).

The results obtained by the proper application of BI techniques depend on the types of data extracted and how they are used. The main factor, however, is the method of transforming raw data into valuable information, not the quantity of data. Therefore, the definition and validation of indicators becomes essential to identify the focus and the data that will be collected. According to the case study by Jin; Kim (2018), for best results, the processes of collecting and analyzing big data and the application of BI should not be separated; they should be integrated and used in a single management decision support system as a whole.

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[4] https://products.office.com/pt-br/excel

[5] https://store.docker.com/editions/community/docker-ce-desktop-windows

[6] https://www.python.org/downloads/

[7] https://code.visualstudio.com/

[8] https://powerbi.microsoft.com/pt-br/

1.2 Problem and relevance of this work

As mentioned previously, the PV-DG market is an international promise and presents numerous possibilities for research or development of new innovative business models. Brazil has been very receptive to this technology. Since the implementation of the first regulatory instrument that allowed small consumers to produce their own energy, the residential sector is the one that has been growing and becoming more popular within the DG market. In this context, a new agent for the electricity sector was born, the prosumer, previously unknown by the utilities and other market agents.

PV solar energy, despite being in constant scientific and technological evolution, is no longer a novelty. The problem that arises along with this growing market is "after-sales", that is, the communication and information management of each new prosumer that has been connecting to the electrical grid, as well as the understanding of the different perspectives involved in the operation.

PV households, as they are considered small systems, often end up being underestimated by the utilities or other market agents. However, today there are already 700 thousand units of PV systems of up to 10 kWp connected to the electrical grid and that together amount to about 3.2 GWp, which represents 32% of the total accumulated (10 GWp) in Brazil (ANEEL, 2022).

In the years 2017 and 2018, under the "Photovoltaic Bonus" program of the local utility CELESC, 1,250 identical PV microgenerators, with individual power of 2.65 kWp, were installed, distributed throughout the State of Santa Catarina (SC) and that together add up to about 3 MWp. In this context, this doctoral thesis aims to evaluate the yield of multiple decentralized PV systems, operating simultaneously, through the proposal of a management and decision-making tool, which adopts BI concepts as research premises. The residential PV roofs were analyzed individually and in groups, divided by regions of the state according to solar irradiation ranges.

As there are different databases and with different irradiation values, the uncertainty that permeates the real generation brings a risk that this generation may not meet the expectation of a PV enterprise and of the investor. For better data reliability, it would be recommended to use ground measurement stations in the areas where the PV generator is intended to be installed, during a historical period similar to the databases used for simulation, something that does not yet exist in Brazil (ANTONIOLLI, 2015; ANTONIOLLI et al., 2014). A set of microgenerators can provide relevant information of the yield of PV-DG systems. By completing a significant period of data collection, this information can assist in mapping solar PV yield in the monitored region.

Database-based simulations of PV generation are not accurate, and anticipating this value is a complex task (CARGNELUTTI FILHO; MATZENAUER; DA TRINDADE, 2004). Therefore, a platform with measured PV generation data in different locations and with significant amounts tends to reduce the risk in forecasting for new generation points, making this value more robust and with a lower degree of uncertainty.

The management of operational data of PV generation (energy and power) from PV roofs, requires first of all the technical treatment to validate this information. The association of a technical algorithm with statistical analyses gives the results greater reliability. This doctoral research uses the accumulated data treatment experience acquired over the years by the Strategic Solar Energy Research Group of the Federal University of Santa Catarina - UFSC, which since 2012 has been participating in the main PV solar energy projects in Brazil, through R&D projects and partnerships with private companies in the sector. In this context, it was identified the need to map and standardize a reliable data processing methodology to be replicated in the technical operational management of PV systems. Moreover, the management of information from these data is still very particular to each manager and the goal of this work is to propose the implementation of a decision-making tool that covers all stages, from data collection, processing, transformation, to the visualization of information through relevant indicators for better decision-making based on measured data and information of theoretical character.

With the current regulations for consumers and utilities (BRASIL, 2022), companies that manage the credits from multiple CUs need to increasingly observe assertiveness in this management to audit consumption data and have the balance of credits generated, ensuring savings and an efficient operation. For companies and consumers registered in the DG models for remote self-consumption and shared generation, for example, there is an additional challenge: managing the multiple CUs that receive credits from the power plants. In these modalities, the generation system is installed in a different location from the CU that will offset the credits.

Parallel to the growing DG market in Brazil, challenges are increasing. Errors are common during the collection and interpretation of PV generation data and in the compensation of electricity credits, but identifying them is not a simple task.

The BI concept makes use of already available information to help managers in the most varied decision making, in a faster and simpler way, through pre-established indicators. The BI flow starts by obtaining and transforming data into information, then into decision making, and finally into useful actions for the business, through indicators and graphics in dashboards (IŞIK; JONES; SIDOROVA, 2013; LIANG; LIU, 2018; TSUNODA, 2014).

The aforementioned problem served as premise and motivation for the development of the methodology of this doctoral thesis, which shows its relevance by contributing to data and information management solutions, using BI tools applied in an unprecedented way to the PV solar energy area and to the case study presented.

1.3 Contribution and innovation

From NR 482/2012 ANEEL, amended by NR 687/2015 ANEEL, the interest in new business models for PV micro and minigeneration has stimulated the production of studies, articles and thesis works in the area, as well as tools for simulation of these systems. The use of BI applications, such as Microsoft's Power BI, for data management of PV systems, despite good adherence, has not been widely used, mainly due to lack of knowledge in the area of PV solar energy by those who already use the application and vice versa, which ensures the originality of this work.

The thesis shows originality regarding the use of PV-DG system databases from CELESC's PEE, the "Photovoltaic Bonus". This information is difficult to obtain due to the secrecy of information by the various actors involved in this project, as well as due to the implementation of the new General Law of Personal Data Protection (LGPD), Law Nº 13,709/2018 (BRASIL, 2018).

Furthermore, the knowledge incorporated in this research to develop technical-statistical algorithms that ensure efficiency and effectiveness in the analysis of PV-DG operational data will help to overcome the lack of knowledge of many managers on how to filter this data based on specialized technical knowledge.

The unprecedented mapping by statistical quartiles using GIS tools to divide the state of Santa Catarina into regions according to irradiation ranges, proves to be a great tool for: (i) identifying locations with better opportunities for investments in PV-DG, and (ii) elaborating strategies for implementation of decentralized power plants considering the productivity of each region.

The novelty of this work also is in the unprecedented use of Energy Business Intelligence (E-BI), for the management of multiple Prosumer Units (PUs) with PV-DG.

Another component of originality is in the improvement of methods for management tools for multiple units of PV-DG systems. The developments of this research will also generate knowledge to enable a series of other innovations, from the application of BI and virtual power plants, for example. The Virtual Power Plants (VPP) (ANTONIOLLI et al., 2020; HERNÁNDEZ, 2015; NIKONOWICZ; MILEWSKI; WARSAW, 2012a; OTHMAN; HEGAZY; ABDELAZIZ, 2015) are configured as an aggregating agent, turning decentralized power generation (consisting of multiple micro and mini generators) into a large virtual plant. Although they are not yet adopted in Brazil, they bring opportunities to reduce risks for small generators and to optimize the management of systems with different sources of power generation (in this case the energy produced by each source is used according to consumer demand).

1.4 Objectives

In the following subtopics, the general objective and the specific objectives of this thesis are presented.

1.4.1 General Objective

The aim of this research was to evaluate the yield of PV systems in the State of Santa Catarina through a management and decision-making tool, capable of efficiently and effectively assessing a large volume of PV microgenerators connected to the distribution grid in a decentralized way.

1.4.2 Specific objectives

To achieve the general objective of the thesis, the following specific objectives were established:

- Obtain a database of the 1,250 distributed microgenerators that were contemplated in CELESC's PEE (PV Bonus) and that were installed throughout the state of SC.
- Divide the state by regions, according to monthly and annual irradiation ranges.
- Map the location of PV generators within the State of SC.
- Use Business Intelligence (BI) concepts for the analysis and management of information.
- Develop a technical-statistical algorithm to filter, analyze and validate a reliable sample of microgenerators.
- Analyze the yield of PV microgenerators installed in different regions throughout the state of SC.
- Simulate theoretical yield, based on satellite databases, for each microgenerator unit under study.
- Compare theoretical and measured yields for each microgenerator in the sample.
- Develop a PV yield abacus for the State of SC, with statistical indicators and mapping by irradiation range.
- Present the energy analysis of one of the prosumer units in the sample.
- Present the socioeconomic impacts of the prosumer, the new agent in the DG market.

1.5 Structure of the thesis

The structure of this thesis was based on Resolution 03/PPGEC/2020. Therefore, this document combines three contextual chapters referring to the Introduction, Discussions and Conclusions with two articles reporting the research, the methods developed, and the results obtained during the Doctoral - The articles are presented through chapters. It is important to note that all co-authors provided a shared authorship agreement, as shown in **Appendix A**. Although the articles have been transcribed into this document, style adjustments have been made to meet ABNT (Associação Brasileira de Normas Técnicas) requirements. In addition, all references are presented at the end of this document.

The first chapter introduces the research topic. Thus, it summarizes the problem and the relevance of this work, its contributions, and innovations, as well as the general and specific objectives.

The second Chapter presents a transcript of an article published in 2022 in the international journal **Sustainable Energy Technologies and Assessments**, with a high impact factor. The article begins with a review of the literature used to develop the first stage of this research, followed by the method, results, and conclusions.

The third Chapter complements the research developed and presented in the previous chapter, through the transcription of a second article published in 2022 in the international journal **Renewable Energy**, with a high impact factor. This chapter also begins with the literature review followed by the method applied to the case study, results, and conclusions.

Finally, the fourth Chapter presents the general conclusions, as well as the limitations of the research and recommendations for potential future developments in this area.

2 YIELD ASSESSMENT OF LARGE ROOFTOP PHOTOVOLTAIC SYSTEM ENSEMBLES

This chapter is the transcription of the following paper:

Development of technical and statistical algorithm using Business Intelligence tools for energy yield assessment of large rooftop photovoltaic system ensembles.

Authored by: Andrigo Filippo Antoniolli, Helena Flávia Naspolini, João Frederico de Abreu and Ricardo Rüther.

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Abstract

The aim of this paper is to develop a methodology for the energy yield assessment of a large ensemble of residential rooftop photovoltaic (PV) generators. The exploration and strategic analysis of data were applied for the first time, through Business Intelligence (BI) concepts combined with a technical-statistical algorithm for 1250 identical distributed rooftop PV systems installed in Santa Catarina, South of Brazil. Tilted solar irradiation maps were divided into four Ranges (statistical-quartiles) and, for the base year of 2019, the case-study results showed, with 95% reliability, an average annual daily energy yield of 3.35 kWh/kWp/day (Range 1); 3.74 kWh/kWp/day (Range 2); 3.82 kWh/kWp/day (Range 3); and 3.90 kWh/kWp/day (Range 4) for the four different quartiles into which the Santa Catarina state surface area was divided. The annual average PV generation of each PV rooftop analyzed was 3,353 kWh/year, which corresponds to an avoided CO_2 emission of 268.25 $kgCO_2$/year. For the combined 1250 PV rooftops ensemble, the average avoided CO_2 emission was 335.30 tCO_2/year. The implementation of BI concepts combined with the technical-statistical algorithm, provided relevant information about the performance of the PV systems, supporting fast decision-making strategies. The methodology applied can be used to predict the monthly/annual generation of future PV ensembles to be installed in any location for distributed generation asset allocation planning.

Keywords: Solar data analysis, PV rooftop, PV energy yield, PV data processing algorithm, Business Intelligence tools

2.1 Introduction

Urban growth increases demand for electricity annually (EPE, 2019) and, alongside this, there are several movements and incentives for the implementation of clean and renewable energy production (BILLIMORIA; HENCHEN, 2020; BODNAR et al., 2020; HORVÁTH; KASSAI-SZOÓ; CSOKNYAI, 2016; IRENA, 2019a; KAPSALIS; KARAMANIS, 2015). In this context, in the last decade, the solar photovoltaic (PV) market has been growing exponentially around the world (GMO, 2020; REN21, 2020); in 2019 the growth was 12% (approximately 115 GW) of an accumulated world total approaching 700 GW by the end of 2020 (REN21, 2020), and 2022 should see solar PV reaching the terawatt installed capacity figure. According to information from the International Renewable Energy Agency (IRENA, 2020), Brazil is one of the fastest-growing PV markets. Photovoltaic solar technology integrated into buildings (PORTOLAN; RÜTHER, 2012; ZOMER et al., 2013; ZOMER; RÜTHER, 2017a) already supplies part of the growing need for electricity in urban regions (BRIGUGLIO; FORMOSA, 2017; FISCHER; SURMANN; BYSKOV, 2020; GAGLIA et al., 2019; JARDIM et al., 2008). In Brazil, in the last five years around 290,000 units of residential PV roof systems have been installed in a decentralized way, with a total installed capacity close to 6 GW and an exponential growth rate (ANEEL, 2021), with the uptake in 2021 alone reaching 2 GW (ANEEL, 2021). Given this promising market scenario, analyzing the volume of performance data resulting from the operation of thousands of new PV generators has become an arduous task. It is common for several of these PV systems to present operational problems, due to a number of possible causes (LIVERA et al., 2019), and there is a lack of reliable methods for the detection and diagnosis of failures in PV system ensembles (MELLIT; TINA; KALOGIROU, 2018). This makes it necessary to create mechanisms for the treatment of operational data of large PV system ensembles connected to the electricity grid, since remotely monitoring the production of PV energy by means of individual PV system sensors is not a trivial task, and the acquisition of these data must be submitted to a rigorous qualification from a technical point of view. (ELSINGA; VAN SARK; RAMAEKERS, 2017; KILLINGER et al., 2016; WU et al., 2015).

One of the methods used for large-scale PV system ensemble data analysis is presented by Heesen and Herbort (HEESEN; HERBORT, 2016), which consists of the removal of unrepresentative PV generator data by means of a statistical filter, and which has already been replicated in PV generator studies in several countries (JORDAN; KURTZ, 2014; LELOUX; NARVARTE; TREBOSC, 2006; POOPPAL, 2017; SEME et al., 2019; TE HEESEN; HERBORT; RUMPLER, 2019). However, it does not present an exactly accurate technical treatment in the elimination of PV systems with failures in the system. This, in turn, reduces the effectiveness of the proposed statistical filters. Another widely disseminated treatment in the data processing literature is gap-filling (SCHWANDT et al., 2014a) which also presents deficiency in the analyses, because it often results in distortion of reality, especially in regions with a very marked climatic variation (PERUCHENA; AMORES, 2017), as is the case of the region under study in this paper, which is located in southern Brazil in a subtropical climate (ALVARES et al., 2013).

There are currently several algorithms for the detection of PV generators with operational problems available in the literature (BAKDI et al., 2019; GUERRERO-LEMUS et al., 2019; HAMADOUCHE; KOUADRI; BAKDI, 2017; LIVERA et al., 2019). However, the implementation of sensors on a large scale becomes impracticable, added to the large computational processing times that these algorithms require. To assist in this task, artificial intelligence is routinely applied in studies to detect operational failures in photovoltaic systems (DHIMISH et al., 2018; ZHAO et al., 2014); meanwhile, the difficulty in training the algorithms is still a barrier. Additionally, there are studies that apply forecasting techniques using satellite measurements of the solar resource availability to assess the performance of PV systems (POLO et al., 2016; SAINT-DRENAN et al., 2016; TADJ et al., 2014); nevertheless, they present high uncertainties when compared to ground measurements (PLATON et al., 2015). The implementation of machine learning techniques for the creation of assessment maps of areas with higher photovoltaic potential is already a reality and has been demonstrated to be an excellent tool (ASSOULINE; MOHAJERI; SCARTEZZINI, 2018; FAZAI et al., 2019). However, due to the fact that it is a recent application, obstacles are still found, such as the lack of shading evaluations (ZOMER; RÜTHER, 2017a, 2017b) and solar radiation input data.

A single PV generator results in large volumes of raw operational data, even at scales with low temporal resolution. For data analysis of the distribution grid of hundreds of PV generators, it is necessary to organize and store them (DU et al., 2018; LIU et al., 2018; RATHORE; CHAUHAN; SINGH, 2019; XU et al., 2018). In this context, major challenges arise, among them, the integration and transformation of raw data into relevant information for control, management, and decision-making. The exploration and strategic analysis of data through the implementation of Business Intelligence (BI) concepts combined with an algorithm, based on technical-statistical methods that allows to evaluate the energy yield of PV systems, can provide managers with relevant information about the performance of such systems.

The BI (Business Intelligence) concept basically consists of providing information already available to support decision-making, quickly, and simply, through pre-established indicators. The BI flow starts with obtaining and transforming data into information, followed by decision making and, finally, resulting in useful actions for the process or business, through indicators and graphs on dashboards (IŞIK; JONES; SIDOROVA, 2013; LIANG; LIU, 2018; TSUNODA, 2014). In the literature review carried out, few types of research with BI applications in the energy area were found.

With the advancement of information technology, as well as due to the increase in data volumes, collection and storage capacity, organizations have been looking for improvements in the processing, visualization, and interpretation of a large volume of information which is being made available daily. The speed and variety in the collection and storage of data increase rapidly, through internal and external resources. This demand has led senior executives to adopt BI tools for the critical analysis and management of their businesses in a more effective way (HAWKING; SELLITTO, 2015; LUFTMAN, 2010). The BI theme is widely used in data analysis research and decision support systems (FARZANEH et al., 2018; IŞIK; JONES; SIDOROVA, 2013; LARSON; CHANG, 2016; RAMAKRISHNAN; JONES; SIDOROVA, 2012). Oprea and Bâra (OPREA; BÂRA, 2014) describe how BI solutions are applied to data regarding the operation of wind farms. Another interesting application of BI was carried out by Firdaus and Amrina (FIRDAUS; AMRINA, 2015), who used the methodology to effectively track and control energy costs. The research addressed the application of data mining obtained through energy auditing applied to an industrial building.

Assouline et al. (ASSOULINE; MOHAJERI; SCARTEZZINI, 2018) estimated the potential for generating PV rooftops on a large scale, using a methodology that combines Geographic Information Systems (GIS) and random PV generation forecasts for a 200 x 200 m² pixel grid covering the entire country, aiming in the future to provide useful information for researchers, service companies, shareholders and other professionals interested in the field of photovoltaic solar energy in buildings. In the literature there are several studies that use GIS to assess the potential of photovoltaic solar energy in urban areas and plot the results visually in the form of maps (AARICH et al., 2018; KHAN; ARSALAN, 2016; ROSAS-FLORES; ZENÓN-OLVERA; GÁLVEZ, 2019; VARDIMON, 2011). From the perspective of the investor, because there are different databases with different solar irradiation values available (MOSCARDINI JR; RÜTHER, 2020), the uncertainty that permeates the real generation brings a risk that this generation may not meet the expectations of a PV enterprise (KARIUKI; SATO, 2018; MOSCARDINI JR; RÜTHER, 2020; PINO et al., 2015). A large amount of relevant data can be highly variable, directly affecting generation results (CARGNELUTTI FILHO; MATZENAUER; DA TRINDADE, 2004). In order to improve data reliability, it is recommended that ground solar energy measurement stations are used. Furthermore, these stations should be located close to the PV generator, and the measured data should be obtained for a historical period similar to the databases used for simulation (ANAGNOSTOS et al., 2019; ERNST et al., 2016; VIANA et al., 2011). This, however is a very high cost solution (ANTONIOLLI, 2015; ANTONIOLLI et al., 2014; GUEYMARD et al., 2020).

There is a consensus in the scientific community that photovoltaic generation in many countries tends to follow a normal distribution, being used even as a criterion for fault detection in photovoltaic arrays (JONES et al., 2017; OGAWA; MORI, 2019). To date, there is a lack of research that simultaneously address both technical and statistical methods for the analysis and treatment of PV system ensemble data.

In the years 2017 and 2018, within the scope of the Photovoltaic Bonus program of the local distribution utility CELESC, 1250 identical residential rooftop PV generators were installed and connected to the low voltage power grid. Each of these dispersed PV systems is rated at 2.65 kWp, distributed throughout the state of Santa Catarina - Brazil, with a total installed capacity of approximately 3.3 MWp. After installation of the PV kits, the project managed a minimum period of monitoring under contract; therefore, the consumer was aware that he could not uninstall the system, nor remove the internet connection until 2019.

The average levels of Global Horizontal Solar Irradiation (GHI) recorded in Brazil are among the best in the world, reaching up to 2234 kWh/m²/year (PEREIRA et al., 2017). The lowest annual solar irradiation averages in the Brazilian territory are recorded in the Southern region of the country, including the state of Santa Catarina (1654 kWh/m²/year), where the experimental data presented here were collected.

As previously described, a number of studies that address data processing to eliminate faulty PV systems were found in the literature (ELSINGA; VAN SARK; RAMAEKERS, 2017; KILLINGER et al., 2016; LIVERA et al., 2019; MELLIT; TINA; KALOGIROU, 2018; WU et al., 2015). However, such studies, in addition to involving considerable computational effort, may present distortions in the real data, especially in regions with high climatic variations. Studies were also found that address only the representativeness of energy yield data from PV systems applied in several countries (Germany, United States, France, India, and Slovenia) (HEESEN; HERBORT, 2016; JORDAN; KURTZ, 2014; LELOUX; NARVARTE; TREBOSC, 2006; POOPPAL, 2017; SEME et al., 2019; TE HEESEN; HERBORT; RUMPLER, 2019). However, these studies did not present data treatment to eliminate faulty PV systems; they only report that the data quality is adequate. In the literature, no study about the energy yield evaluation of large-scale distributed generation PV systems in Brazil was found.

To guarantee the technical quality of the generation data of each analyzed PV system, this paper adopted technical filters for the validation of daily, monthly, and annual data. Additionally, to guarantee the representativeness of the PV generation data, it used a statistical algorithm whose objective is to identify outliers to provide a normal distribution for the energy yield of the sample.

The adoption of both technical and statistical filters allows defective PV systems and PV systems with non-representative generation data to be excluded from the analyzed sample, avoiding the treatment of data via gap-filling and the use of ground measurement stations next to the PV generator.

As Oprea and Bâra (OPREA; BÂRA, 2014) explored BI concepts in an unprecedented way when evaluating wind farm operation data, this paper proposes to analyze, for the period between January and December 2019, the monthly and annual energy yield of PV rooftop systems ensembles using applications of BI entitled Energy Business Intelligence (E-BI), combined with a technical-statistical algorithm to assess the solar energy yield of such systems as an ensemble. For the technology and location analyzed, the results presented visually on maps using GIS tools are novel, and they should be helpful to assist plant operators/owners in decision making and to analyze whether their photovoltaic systems are operating properly or if they need repair for malfunction.

2.2 Method

The 1250 identical rooftop PV kits are composed of 10 PV modules and one inverter. Tables 2.1 and 2.2 present respectively, the characteristics of the PV modules and the inverter.

Table 2.1. PV modules characteristics (JAP6-60-265/4BB).

Technology	**Power (W)**	**Vmpp (V)**	**Impp (A)**	**Voc (V)**	**Isc (A)**
Multicrystalline Silicon (p-Si)	265	138	17	38.05	9.08

Table 2.2. Inverter characteristics *(*UNO-3.0-TL-OUTD).

Inverter Power	**Absolute max. DC input voltage (Vmax,abs)**	**Start-up DC voltage (Vstart)**	**Max. DC input current**	**MPPT input DC voltage range**	**Number of independent MPPT**
3 kW	600	100...300 V (default 150 V)	16.0 A	200...500 V	1

The monitoring of this study was done via internet connection. All inverters are connected to the same platform, available from the manufacturer, ABB Aurora Vision® Plant Management Platform. Data were periodically extracted using Python algorithms and organized in Microsoft Excel VBA (Visual Basic for Applications) spreadsheets to later integrate with a Microsoft Power BI® tool.

BI components are divided into four main stages: (i) Operational data and raw data; (ii) ETL (extraction, transformation, and loading) processes; (iii) Data Warehouse: storage of data already organized and processed; (iv) Visualization of results: indicators, graphs, and dashboards. The exploration and strategic analysis of data adopted in this paper follows the steps of the BI methodology. The application of this process for the analysis of irradiation and solar PV generation data added to the knowledge of the area of electrical energy systems, resulted in the E-BI method. Figure 2.1 shows the block diagram of the systematic method of the decision-making assistance tool that converts raw data into useful information on the energy yield of an ensemble of PV rooftops connected to the electrical distribution grid.

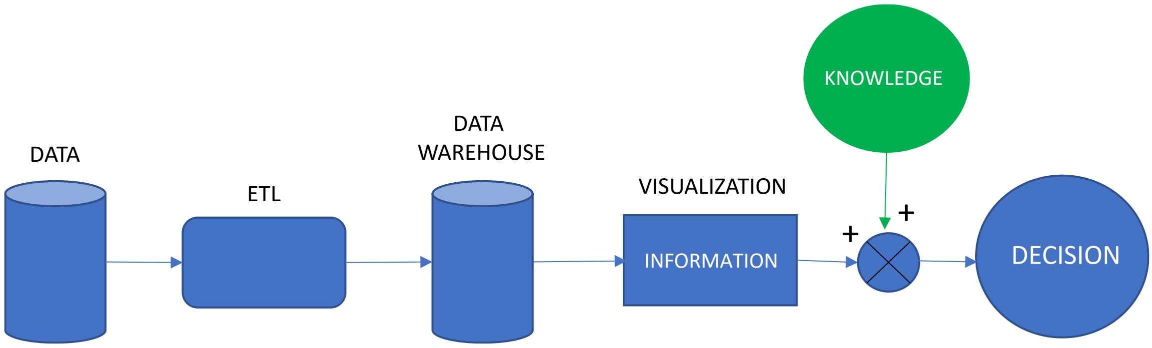

Figure 2.1. Block diagram of the E-BI methodology to support decision making in the management and planning of multiple photovoltaic systems connected in a distributed generation grid.

Visualization of technical information combined with knowledge supports decision making by technical professionals involved in the operation or administration of multiple PV systems connected in a distributed generation grid.

In the 12 months of 2019, photovoltaic generation data (at 5-minute intervals) of the 1250 identical rooftop PV systems with an installed power of 2.65 kWp per unit, were monitored remotely by the ABB Aurora Vision® Plant Management Platform[9]. These data were extracted via the internet and stored in a raw database. The flowchart of the technical-statistical algorithm adopted in this work, shown in Figure 2.2, is divided into six stages, namely: (i) Input: raw PV generation database; (ii) Technical Filter: in this stage, PV systems with data collection problems or which do not meet the adopted technical requirements are discarded; (iii) Technical transformation: the PV systems data selected by the technical filter are transformed into energy yield indicators; (iv) Statistical Filter: in this stage, outliers are removed, eliminating PV systems that differ from the sample; (v) Statistical transformation: calculates the sample's statistical indicators; (vi) Output: database treated and validated for systems performance analysis.

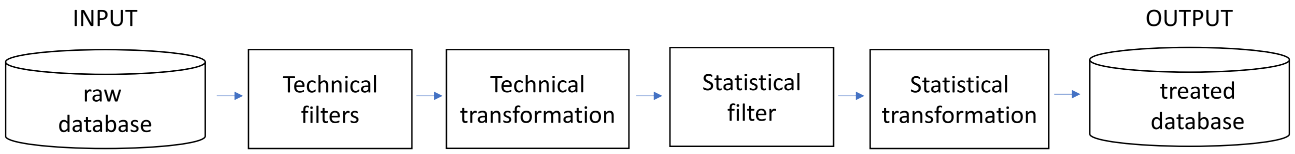

Figure 2.2. Flowchart of the technical-statistical algorithm.

2.2.1 Technical filters and technical quality of data

Among the large volume of raw data existing on the ABB Aurora Vision® platform, each PV system unit registered in the system was identified and the individual values of photovoltaic power were extracted, with a temporal resolution of 5 minutes, expressed in kW. Before the application of technical filters, these records were integrated and transformed into photovoltaic energy records, on an hourly basis, expressed in kWh.

To guarantee the technical quality of the measured data of each PV generator, that is, to automatically identify and neglect data with incorrect values (from systems with technical failures or defective data communication system), the following premises were adopted:

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[9] www.fimer.com/sites/default/files/AURORA_VISION_PLANT_MANAGEMENT_PLATFORM_BCD.00666_EN_Rev.B_0.pdf

i. **Validation of daily PV generation data:** PV systems that have at least 8 hours or more of records (equivalent to a day with at least 8 hours of PV generation) and minimum PV power of 50 W are counted, and the individual data are validated and registered for the PV generation (kWh) for that day.
ii. **Validation of monthly PV generation data:** PV systems that present at least 15 days of daily data validated by the filter (i) are counted.
iii. **Validation of annual PV generation data:** PV systems that have validated monthly PV generation data records (by filters (i) and (ii)) in the 12 months of the analyzed period are counted.

Figure 2.3 presents the block diagram adopted for the technical filters applied to the PV generation data of each PV generator.

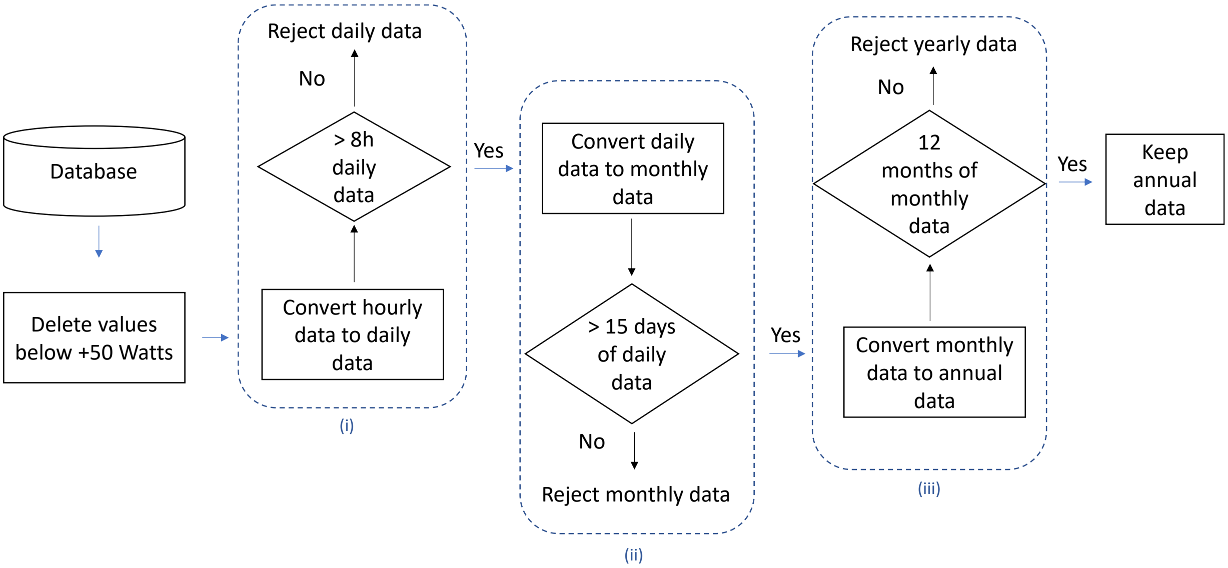

Figure 2.3. Block diagram of technical filters applied to the PV generation data.

2.2.2 Technical transformation

In this stage, the PV generation data for each PV generator is transformed into daily energy yield indicators, within the specified time interval, expressed in kWh/kWp/day, as shown in Equation 2.1.

$$\mathrm{Y_i} = \frac{\mathrm{E_{FVi}}}{\mathrm{N}*\mathrm{P_{FVi}}} \qquad \text{(Eq. 2.1)}$$

where:

Y_i = Average daily energy yield of the PV generator i, within the specified time interval, in kWh/kWp/day

E_{FVi} = Solar generation of the PV generator i, in the specified time interval (month or year), in kWh

P_{FVi} = Installed power of the PV generator i (2.65 kWp).

N= Number of valid days in the specified time range.

2.2.3 Statistical filter and data significance

Figure 2.4 presents for the state of Santa Catarina, an annual daily average (17 years) of the global latitude-tilt irradiation from the sample of 1000 georeferenced coordinates with spatial resolution of 0.1 x 0.1 degrees (approximately 10 x 10 km), presented through the Geographic Coordinate System SIRGAS1 2000 by the Brazilian Atlas of Solar Energy (PEREIRA et al., 2017), divided into four irradiation ranges (four statistical quartiles), named as irradiation ranges # 1, 2, 3 and 4, with values ranging from 1380 to 1560 kWh/m²/year (1st Quartile, equivalent to 3.78 to 4.28 kWh/m²/day), 1560 and 1635 kWh/m²/year (2nd Quartile, equivalent to 4.28 to 4.48 kWh/m²/day), 1635 and 1730 kWh/m²/year (3rd Quartile, equivalent to 4.48 to 4.74 kWh/m²/day) and 1730 and 1800 kWh/m²/year (4th Quartile, equivalent to 4.74 to 4.95 kWh/m²/day). In order to plot this map, GIS mapping from the Microsoft Power BI® tool was used.

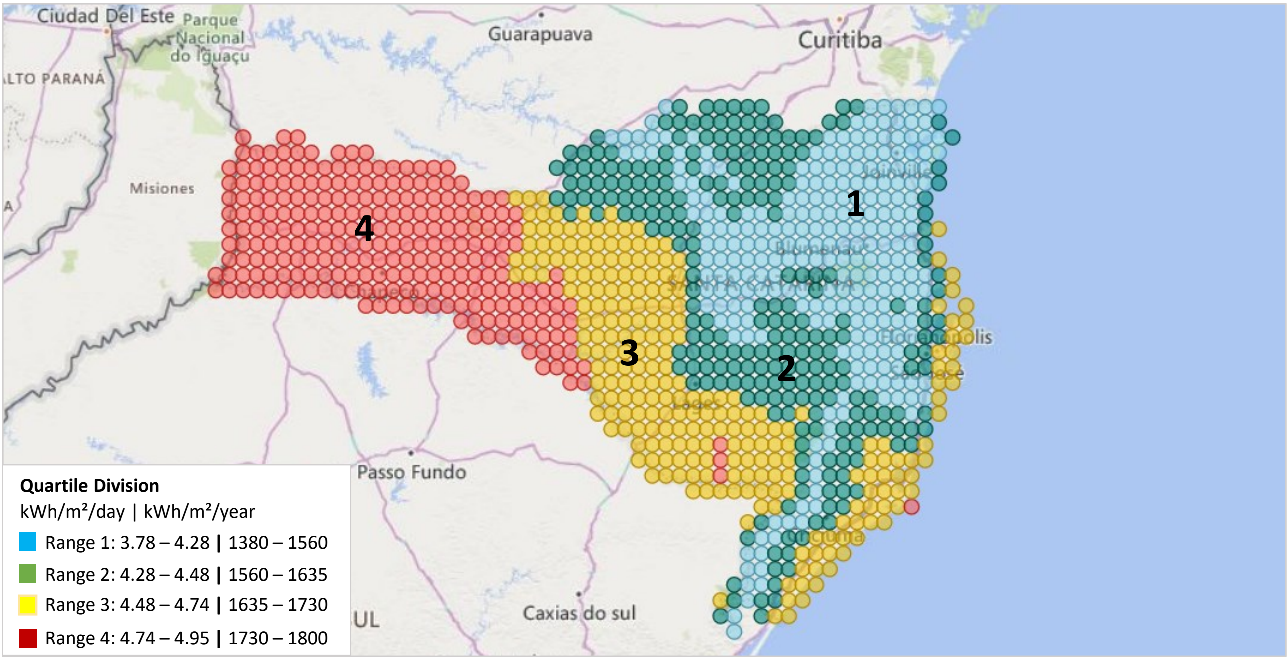

Figure 2.4. Global annual tilted irradiation in the State of Santa Catarina, Brazil, divided by ranges (quartiles).

For each range of tilted solar irradiation, by identifying the location of each PV generator, the corresponding theoretical PV energy yields were calculated to compose the sample required for the application of statistical filters. It should be noted that this filter is applied to the sample of PV systems selected from the application of technical filters previously described.

To guarantee the quality and significance of the measured energy yields for the analyzed PV generators set, the Interquartile Range method was applied (HEESEN; HERBORT, 2016). In this case, the objective is to eliminate implausible values from the distribution curve of the measured yields. The focus of the algorithm is to eliminate outliers automatically and ensure a normal distribution of the measured productivity for the set of analyzed PV systems. In this evaluation metric, the median and quartiles are relevant indicators. The median is a position that ensures that 50% of the measured values are smaller and 50% of the measured values are larger. Quartiles divide a data set into four equal parts. In the lower quartile (1st quartile), 25% of the measured values are lower and 75% of the measured values are higher than the 1st quartile. In the upper quartile (3rd quartile), 75% of the measured values are lower and 25% of the measured values are higher than the 3rd quartile. The distance between the first and the third quartiles is called the "interquartile range (IQR)". Beyer (1981) (BEYER, 1981) defines as false values those outside the range of about 1.5 * IQR. This range is called “whisker distance”.

Equations 2.2 to 2.4 show, respectively, the "interquartile range (IQR)" and the upper and lower limits of the "whisker distance".

$$\mathrm{IQR} = \mathrm{Q}_3 - \mathrm{Q}_1 \qquad \text{(Eq. 2.2)}$$

$$\mathrm{L}_\mathrm{s} = \mathrm{Q}_3 + 1.5 \cdot \mathrm{IQR} \qquad \text{(Eq. 2.3)}$$

$$\mathrm{L}_\mathrm{i} = \mathrm{Q}_1 - 1.5 \cdot \mathrm{IQR} \qquad \text{(Eq. 2.4)}$$

where:

Q_1 = First quartile

Q_3 = Third quartile

IQR = Interquartile Range

L_s = upper threshold of "*whisker distance*"

L_i = Lower threshold of "*whisker distance*"

The statistical filter identifies, through the Interquartile Range method (HEESEN; HERBORT, 2016), the discrepant points of each group of PV generators, which were divided by irradiation ranges, and eliminates them, in order to find a more adjusted normal distribution. The filter has a repetitive behavior, according to the algorithm presented in the block diagram shown in Figure 2.5.

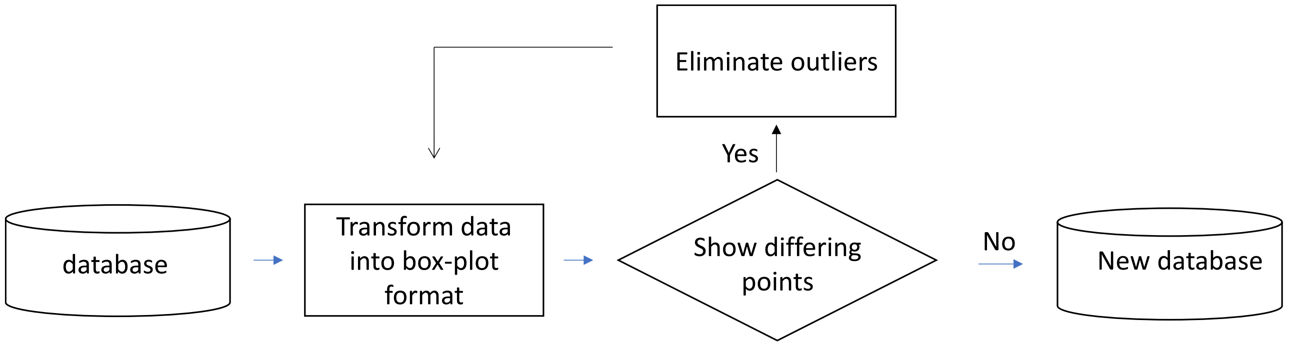

Figure 2.5. Block diagram of Statistical filter.

2.2.4 Statistical transformation

The significance of the data was analyzed using the distribution normality test, which adopted the QQ-plot (R^2) method. In this case, measured energy yield data were correlated with data from a normal distribution. For a correlation greater than 0.9 the sample is characterized as a normal distribution.

The normal distribution, the arithmetic mean, the standard deviation, and the sample's margin of error (95% reliability) can be calculated as shown in Equations 2.5 to 2.7.

$$M_a = \frac{\sum_{i=1}^{N} x_i}{N} \qquad \text{(Eq. 2.5)}$$

$$S = \sqrt{\frac{\sum_{i=1}^{N} (x_i - M_a)^2}{N}} \qquad \text{(Eq. 2.6)}$$

$$\text{Erro} = Z_{\frac{\propto}{2}} \frac{S}{\sqrt{N}} \qquad \text{(Eq. 2.7)}$$

where:

$1<i<n$

N = Number of sample PV systems (ensemble size)

x_i = Energy yield value of each PV system i

Ma = Yields arithmetic mean

S = Standard deviation of the energy yield set of PV systems (ensemble)

Erro = sample error

α = Significance level (0.05), typically used for energy yield analysis (HEESEN; HERBORT, 2016)

$Z_{\alpha/2}$ = Table Z value associated with α ($Z_{0.025}$=1.96)

The calculation of the normal distribution of an ensemble of elements is performed from the correlation (R) between a theoretical normal sample (created from the average and standard deviation data of the analyzed ensemble) and a real sample. If this squared correlation value (R^2) is greater than 90%, it is a strong indicator that the real sample distribution corresponds to a normal distribution. If the average ensemble value is equal to the median, it is also possible to prove the existence of a normal distribution, this indicator can be visualized through a box-plot graph.

2.2.5 Calculation of measured energy yield from the valid ensembles

After running the PV generation data of each PV generator through the technical-statistical filters, the average daily generation measured for each individual PV generator can be obtained from the sum of the energy generated in the valid days within the specified time interval divided by the number of valid days, as shown in Equation 2.8.

$$\mathrm{EFVi}_{\mathrm{average}} = \frac{\sum_{1}^{N} \mathrm{E_i}}{\mathrm{N}} \qquad \text{(Eq. 2.8)}$$

where:

$\mathrm{EFVi}_{\mathrm{average}}$ = Average daily PV energy measured, in the specified time interval, in kWh;

Ei = Average daily PV energy measured on valid days, in kWh;

N = Number of valid days.

The measured energy yield of each individual PV generator will be based on the average daily PV solar energy measured divided by the installed power value (2.65 kWp), as shown in Equation 2.9.

$$\mathrm{Yi} = \frac{\mathrm{EFVi}_{\mathrm{average}}}{\mathrm{P_{FV}}} \qquad \text{(Eq. 2.9)}$$

where:

Yi= Average measured daily PV energy yield, in the specified time interval i, in kWh/kWp;

$\mathrm{EFVi}_{\mathrm{average}}$ = Average measured daily PV solar energy generated, kWh;

$\mathrm{P_{FV}}$ = Installed PV power, in kWp.

For each range of latitude-tilted irradiation analyzed (quartile), the quality and significance of the measured data used in the calculations of the measured yield was guaranteed through the application of the methodology presented in technical-statistical algorithm.

2.2.6 Calculation of theoretical yield

Data: Latitude-tilt solar irradiation and photovoltaic generation

In this paper, data for latitude-tilted solar irradiation (GTI) from the Brazilian Solar Energy Atlas, made available by the Brazilian National Space Institute (*Instituto Nacional de Pesquisas Espaciais – INPE* in Portuguese) in CSV format were obtained. The spatial resolution is 0.1 ° x 0.1 ° (approximately 10 x 10 km) and is presented through the SIRGAS1 2000 geographic coordinate system. The state of Santa Catarina has 1000 points of global horizontal solar irradiation distributed throughout its territory (PEREIRA et al., 2017).

In the 12 months of 2019, individual PV generation data from 1250 PV generators with a total installed capacity of 3.25 MWp were measured, remotely monitored by the manager ABB Aurora Vision® Plant Management Platform[10]. The raw data and information related to each microgenerator were stored in the cloud, which allowed real-time visualization of the operating values of the registered PV systems. Among the large volume of data on the platform, each microgeneration unit registered in the monitoring system was identified and the individual values of photovoltaic power were extracted, with a temporal resolution of 5 minutes, expressed in kW. PV solar energy, at 5-minute intervals, was calculated according to Equation 2.10.

$$\mathrm{E_{FV}} = \mathrm{P} \times \frac{5}{60} \tag{Eq. 2.10}$$

where:

E_{FV} = PV energy, in 5-minute intervals, in kWh;

P = Recorded power, at 5-minute intervals, in kW.

The PV energy, in the specified time interval, can be obtained through Equation 2.11.

$$\mathrm{EFV_i} = \sum_{\mathrm{k=1}}^{\mathrm{i}} \mathrm{EFV_k} \tag{Eq. 2.11}$$

where:

EFV_i = PV energy in the specified time interval i (hourly), in kWh;

EFV_k = PV energy, in the time interval k integral of the specified time interval i, in kWh;

i = Upper limit of the sum;

k = Lower limit of the sum.

For the state of Santa Catarina, from the GTI data made available by the Brazilian Solar Energy Atlas, a statistical analysis of solar irradiation in the tilted plane was carried out. It was observed that in all statistical quartiles (1st to 4th quartile) their distribution is equivalent to a normal distribution. Monthly maps and the annual map of tilted irradiation in Santa Catarina were prepared, divided into four Ranges (four statistical quartiles) of solar irradiation on the tilted plane. Based on geographical coordinates, each PV generator was located on the latitude-tilt Santa Catarina state solar irradiation map.

Through the geographic coordinates (Latitude and Longitude) of each PV generator, identified by an identifier code (ID), the values of the latitude tilted irradiation were obtained, and the corresponding theoretical

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[10] www.fimer.com/sites/default/files/AURORA_VISION_PLANT_MANAGEMENT_PLATFORM_BCD.00666_EN_Rev.B_0.pdf

energy yields were calculated, using the weighted average between the four closest points, georeferenced and identified in the data extraction process.

Figure 2.6 shows the positioning of four points in the database and an unknown point (Px), which represents the location of the PV generator under analysis. Each PV generator was inserted in its corresponding irradiation range (corresponding quartile).

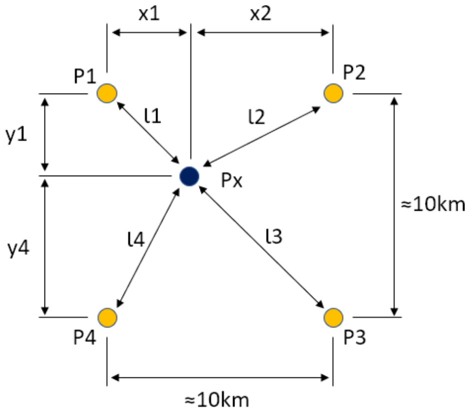


Figure 2.6. Positioning the point of the PV generator (P_x) between the reference points.

Equations 2.12 to 2.15 show the calculations that must be carried out in order to obtain solar irradiation values on the latitude-tilted plane at point P.

$$L_i = \sqrt{(Lat_i - Lat_p)^2 + (Lon_i - Lon_p)^2} \qquad \text{(Eq. 2.12)}$$

$$L_{total} = L_1 + L_2 + L_3 + L_4 \qquad \text{(Eq. 2.13)}$$

$$R_i = \frac{L_{total}}{L_i} \qquad \text{(Eq. 2.14)}$$

$$G_p = \frac{G_1.R_1+G_2.R_2+G_3.R_3+G_4.R_4}{R_1+R_2+R_3+R_4} \qquad \text{(Eq. 2.15)}$$

where:

L_i = L_1, L_2, L_3, L_4 = Distance from Px to Pi

R_i = R_1, R_2, R_3, R_4 = Dimensional reference

G_p = Solar irradiation value in the latitude-tilted plane at point P

Lat_i = Latitude at point i

Lon_i = Longitude at point i

Lat_p = Latitude at point X

Lon_p = Longitude at point X

The theoretical energy yield represents the expected value of the amount of PV energy that would be generated per unit of installed power (kWh / kWp) and can be estimated through Equation 2.16.

$$\mathrm{Yi} = \mathrm{PR} \times \frac{\mathrm{GTI_i}}{\mathrm{Irr_{STC}}} \qquad \text{(Eq. 2.16)}$$

where:

Yi = Yield of the PV generation, in the specified time interval i, in kWh/kWp;

PR = Theoretical Performance Ratio

GTIi = Latitute-tilted irradiation, in the specified time interval i, in kWh/m²

IrrSTC = Irradiance under Standard Test Conditions (1 kW/m²).

For theoretical Performance Ratio (PR) the typical value of 80% was adopted (MARION et al., 2005; REICH et al., 2012; RÜTHER; VIANA; SALAMONI, 2010).

2.2.7 Comparison between Theoretical and Measured Yield

To validate and plot an energy yield map dashboard for the state of Santa Catarina, the Theoretical Energy Yield values (based on a database available by satellite) were compared with Measured Energy Yield values (sample of PV rooftops). Each region (Range/Quartile) has an ensemble of monitored PV systems that have been compared with the estimated theoretical value for the location.

2.2.8 CO_2 emissions avoided

The avoided emissions of greenhouse effect gases, expressed in tons of equivalent CO_2, are the main technical indicators to assess the environmental impacts provided by the surplus electricity into the grid (NASPOLINI; RÜTHER, 2012; UUSITALO et al., 2017). This paper analyzed the adoption of solar PV generation by the residential consumer. Avoided CO_2 emissions, in the period i, were calculated according the Brazilian electrical sector (MCTIC, 2019), using Equation 2.17, for the period between January and December 2019.

$$\mathrm{CO_{2i}} = \mathrm{EPV_i} \times \mathrm{F_i} \qquad \text{(Eq. 2.17)}$$

where:

CO_{2i} = Avoided greenhouse gas emissions in period i, in $tCO_{2equivalents}$;

EPV_i = PV energy generated in period i, in MWh;

F_i = Average emission factor of the Brazilian Interconnected Energy System - SIN, in period i, in tCO_2/MWh.

Table 2.3 presents, for the Brazilian Interconnected Energy System - SIN generation mix, and for the period between January and December 2019, the inventory of the average equivalent CO_2 emission factors, expressed in tons of CO_2/MWh, calculated, and made available by the Brazilian SIN. Calculations consider the fossil fuel-based participation in Brazilian electricity production at the SIN.

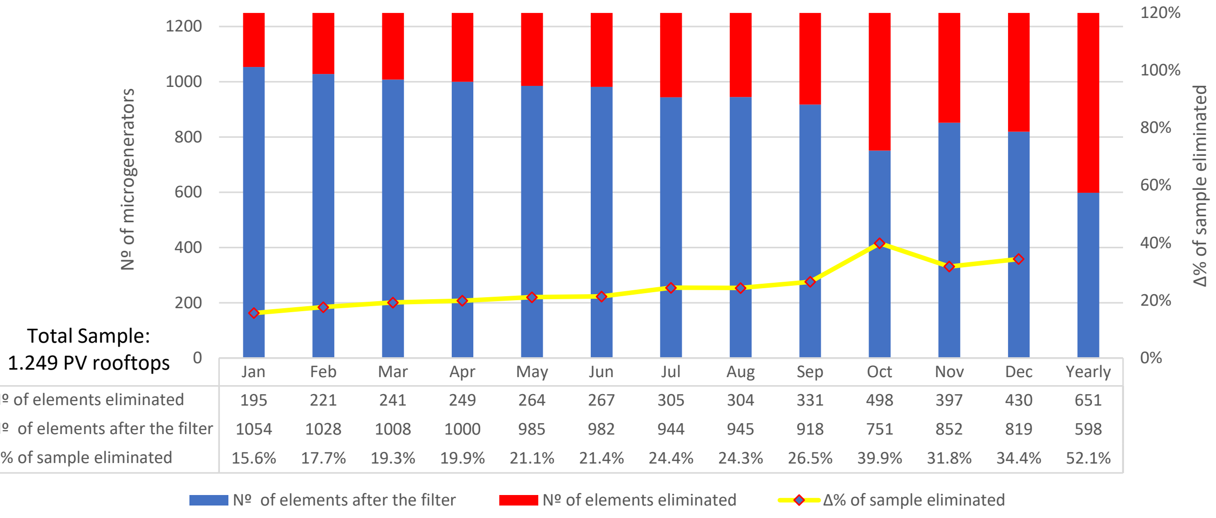
Table 2.3. Average emission factors of CO_2 (tCO_2/MWh) – Base year 2019. Source: (MCTIC, 2019).

Monthly											
JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0.0355	0.0667	0.053	0.0514	0.0482	0.0426	0.0906	0.107	0.1024	0.104	0.1078	0.0913

2.3 Results

2.3.1 Impacts provided by the application of technical filters

Figure 2.7 shows the monthly evolution of the sample of PV generators after the application of technical filters. The bars show the number of elements eliminated and elements remaining in the sample (vertical left axis). The yellow line shows, in percentage values, the number of elements (PV generators) eliminated from the sample (vertical right axis).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
Nº of elements eliminated	195	221	241	249	264	267	305	304	331	498	397	430	651
Nº of elements after the filter	1054	1028	1008	1000	985	982	944	945	918	751	852	819	598
Δ% of sample eliminated	15.6%	17.7%	19.3%	19.9%	21.1%	21.4%	24.4%	24.3%	26.5%	39.9%	31.8%	34.4%	52.1%

Figure 2.7. Monthly evolution of PV generators subjected to technical filters.

Throughout 2019, there was a gradual increase in the number of PV generators which had to be discarded by technical filters, with a peak of 39.9% (498 PV generators) in October. January presented the best result, with 195 PV generators eliminated by technical filters (15.6%). In the 12 months of 2019 the results showed that 52.1% (651 units) of the PV generators analyzed were discarded for presenting operational problems, resulting in a sample of 598 valid identical PV systems.

It can be clearly seen that lack of maintenance has led to a considerable fraction of these PV generators to underperform, which is important to be noted and avoided. These results show the importance of adopting an efficient operations and maintenance management system to control the operation and the data acquisition system of an ensemble of PV generators simultaneously. Ensuring the accuracy of this large volume of data is not an easy task, and to perform this type of analysis manually, in addition to making the process inefficient, might lead to the results not achieving the desired effectiveness. In this context, the technical filters adopted proved to be very efficient to assist in the first stage of selection of the PV generators ensemble used in this research.

The technical filters adopted in this work can be integrated with the data acquisition platform to perform the selection of PV systems that meet technical requirements in real time, thus facilitating the decision-making of managers of an ensemble of generating units or decentralized plants composed of more than one generator connected to the distribution grid.

Figure 2.8 shows a GIS map, plotted by Microsoft Power BI®, with blue dots for the approved PV systems, and red dots for those discarded by technical filters.

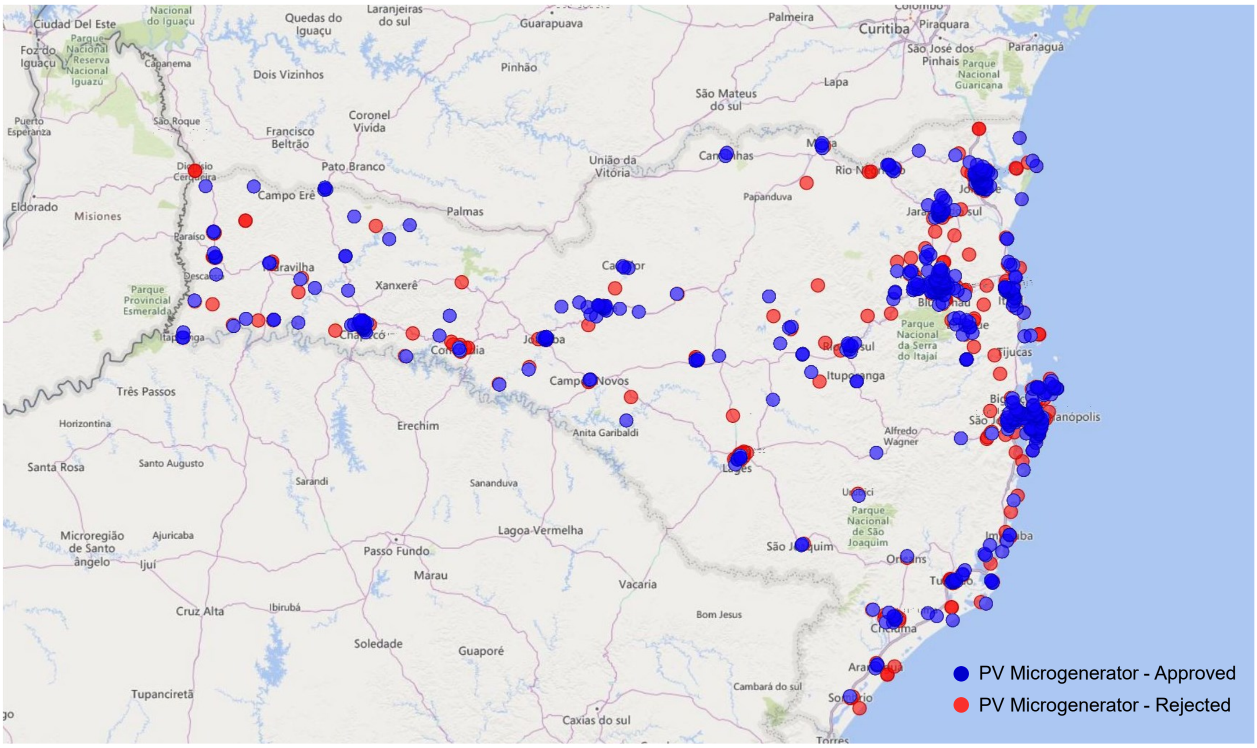
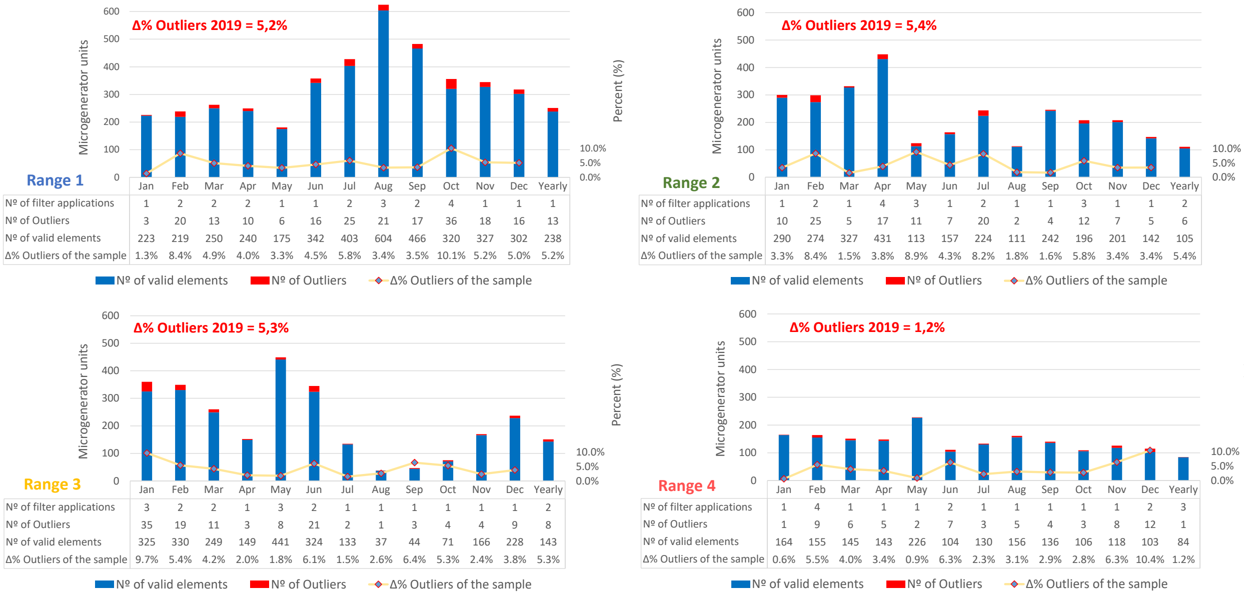


Figure 2.8. Coordinates of passed (blue dots) rooftop PV generators and those rejected (red dots) by technical filters.

As shown in Figure 2.8, when superimposing the position of the sample of valid PV systems (598 PV roofs) with the sample of PV systems discarded by technical filters (651 PV roofs), it is noted that, even with 52.1% less PV generators than the initial total sample (1249 PV roofs), PV generators with valid data and suitable for operational analysis remain well distributed throughout the analyzed territory, thus allowing the assessment of the measured energy yield of rooftop PV systems throughout the whole area shown in the map.

2.3.2 Impacts provided by the application of the statistical filter

For each sample of PV generator located in each latitude-tilt solar irradiation range (four irradiation ranges = four statistical quartiles previously presented), the statistical filter was applied after the application of technical filters. Figure 2.9 shows, for the four ranges of latitude-tilt solar irradiation levels in Santa Catarina - Brazil, the monthly evolution, and the annual behavior of the sample. The bars represent the number of valid PV generators (blue) and the number of outliers (red). The percentage value of PV generators which were eliminated from the sample is shown in the yellow line.



Range 1

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
Nº of filter applications	1	2	2	2	1	1	2	3	2	4	1	1	1
Nº of Outliers	3	20	13	10	6	16	25	21	17	36	18	16	13
Nº of valid elements	223	219	250	240	175	342	403	604	466	320	327	302	238
Δ% Outliers of the sample	1.3%	8.4%	4.9%	4.0%	3.3%	4.5%	5.8%	3.4%	3.5%	10.1%	5.2%	5.0%	5.2%

Range 2

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
Nº of filter applications	1	2	1	4	3	1	2	1	1	3	1	1	2
Nº of Outliers	10	25	5	17	11	7	20	2	4	12	7	5	6
Nº of valid elements	290	274	327	431	113	157	224	111	242	196	201	142	105
Δ% Outliers of the sample	3.3%	8.4%	1.5%	3.8%	8.9%	4.3%	8.2%	1.8%	1.6%	5.8%	3.4%	3.4%	5.4%

Range 3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
Nº of filter applications	3	2	2	1	3	2	1	1	1	1	1	1	2
Nº of Outliers	35	19	11	3	8	21	2	1	3	4	4	9	8
Nº of valid elements	325	330	249	149	441	324	133	37	44	71	166	228	143
Δ% Outliers of the sample	9.7%	5.4%	4.2%	2.0%	1.8%	6.1%	1.5%	2.6%	6.4%	5.3%	2.4%	3.8%	5.3%

Range 4

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
Nº of filter applications	1	4	1	1	1	2	1	1	1	1	1	2	3
Nº of Outliers	1	9	6	5	2	7	3	5	4	3	8	12	1
Nº of valid elements	164	155	145	143	226	104	130	156	136	106	118	103	84
Δ% Outliers of the sample	0.6%	5.5%	4.0%	3.4%	0.9%	6.3%	2.3%	3.1%	2.9%	2.8%	6.3%	10.4%	1.2%

Figure 2.9. Monthly evolution of PV generators passed in the statistical filter in the four-irradiation ranges.

In the analyzed period, the results show that the application of the statistical filters after the application of the technical filters, removed less than 10% of outliers, except in the months of October for a representative sample of the PV generators located in Range 1 (10.11%) and December for a representative sample of PV generators located in Range 4 (10.43%).

In general, it was necessary to apply two cycles of the statistical filter so that there was no discrepancy in the data in relation to a normal statistical distribution. Four cycles of the statistical filter were applied in the months of October (Range 1), April (Range 2) and February (Range 4). The percentage values of outliers after the application of statistical filters were 5.2% (Range 1), 5.42% (Range 2), 5.3% (Range 3), 1.2% (Range 4). The total number of PV rooftops (after applying the technical-statistical algorithm presented in this work) used to evaluate the PV energy yield of PV generators in Santa Catarina - Brazil was 570 units. The monthly maps (Jan to Dec) of the average daily latitude-tilt solar radiation from satellite data and the monthly evolution of the measured average daily yield are presented in Figures 2.19 to 2.30.

2.3.3 Normality test and sample error level

Figure 2.10 shows for the 570 PV generators (solid lines) the coefficients of determination between the distribution curve of the measured energy yields and the theoretical normal distribution curve. Additionally, bars on the right-hand vertical axis present the percentage error margins for 95% reliability.

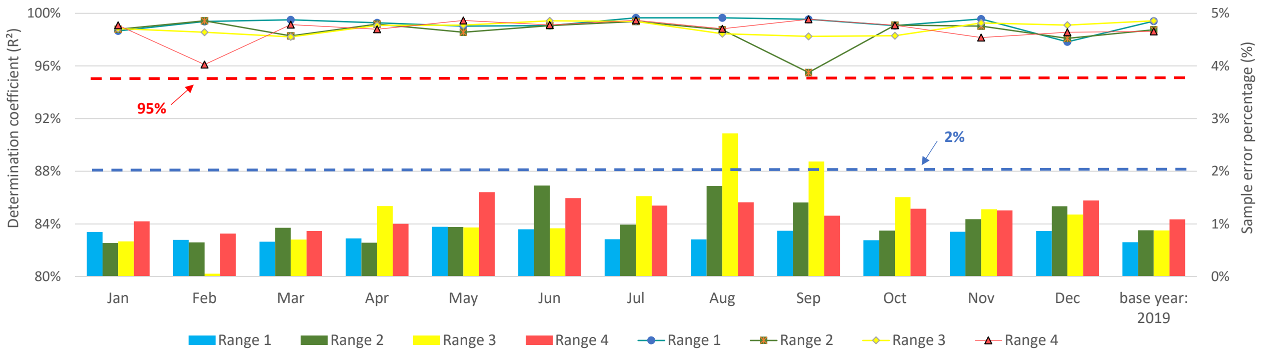


Figure 2.10. Coefficients of determination between the analyzed sample and theoretical sample of normal distribution (in lines) and percentages of error margin (in bars).

For the energy yields, each PV generator sample located in each range of tilted solar irradiation (four Ranges), high values of determination coefficients (above 95%) was observed. In September, the coefficient of determination was 95.5% (Range 2), and in December it was 97.8% (Range 1). In the remaining months, the values of the determination coefficients were larger than 98.0%. In the analyzed period, the percentage values of the error margin of the PV generator samples were less than 2% (blue line), except in August and September, months in which the error margins were respectively 2.7% and 2, 2% for the sample of PV generators located in Range 3.

2.3.4 Normal Distributions

Figure 2.11 shows for the year 2019 and for the four Ranges of latitude-tilt solar radiation from Santa Catarina - Brazil, the measured energy yield normal distribution curves, and Figure 2.12 details the values of the same in a box-plot graph. The results presented were based on the measured data of PV generation of the 570 identical rooftop PV systems, validated by the technical-statistical algorithm proposed in this work.

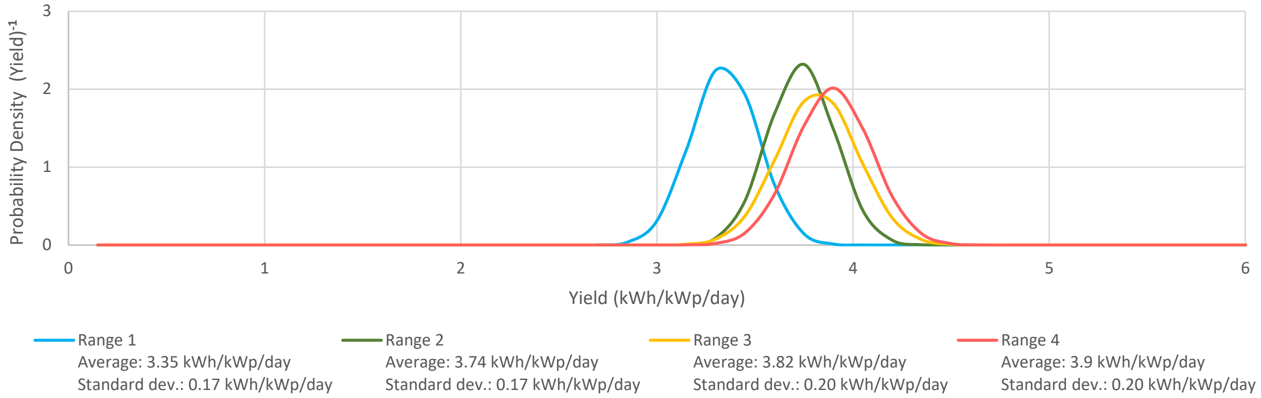


Figure 2.11. Measured energy yield distribution curves. Base year: 2019.

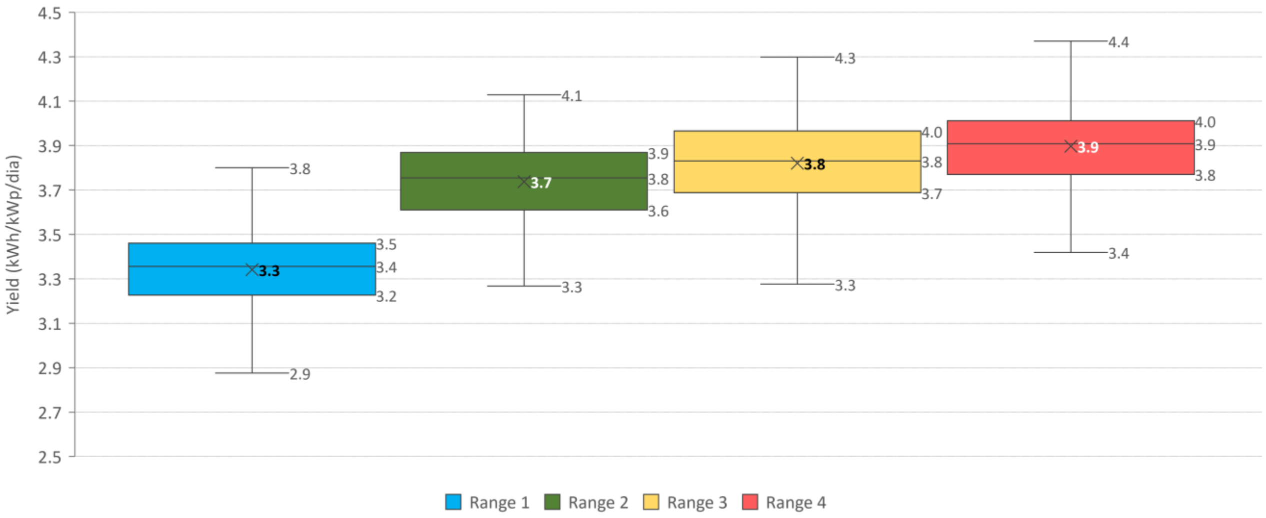


Figure 2.12. Measured energy yield boxplot graph. Base year: 2019.

The results show, with 95% reliability, that the energy yield values for each of the four ranges analyzed were:

Range 1: Average yield of 3.35 kWh/kWp/day (1223 kWh/kWp/year), with values varying between 2.9 and 3.8 kWh/kWp/day (1060 and 1390 kWh/kWp/year).

Range 2: Average yield of 3.74 kWh/kWp/day (1365 kWh/kWp/year), with values varying between 3.3 and 4.1 kWh/kWp/day (1205 and 1495 kWh/kWp/year).

Range 3: Average yield of 3.82 kWh/kWp/day (1395 kWh/kWp/year), with values varying between 3.3 and 4.3 kWh/kWp/day (1205 and 1570 kWh/kWp/year).

Range 4: Average yield of 3.90 kWh/kWp/day (1423 kWh/kWp/year), with values varying between 3.4 and 4.4 kWh/kWp/day (1240 and 1605 kWh/kWp/year).

In the analyzed period, it is observed that the mean and the median present very similar values in all the analyzed ranges. It is also noticed that Range 1 stands out from the other bands for presenting the lowest average daily yield. The curves for Ranges 1 and 2 are more pronounced, as they have less variability (standard deviation = 0.17), that is, they represent groups of PV generators with more homogeneous energy yields. The groups of PV generators located in Ranges 3 and 4, on the other hand, despite having higher energy yields, present curves with a flatter shape due to the greater standard deviation (0.20).

Figure 2.13 shows methodology described in this paper applied to the case-study in State of Santa Catarina in the South of Brazil. The GIS map presents the annual average daily latitude-tilted solar irradiation on the left, and the same area divided in annual average daily latitude-tilted irradiation quartiles, in kWh/m²/day.

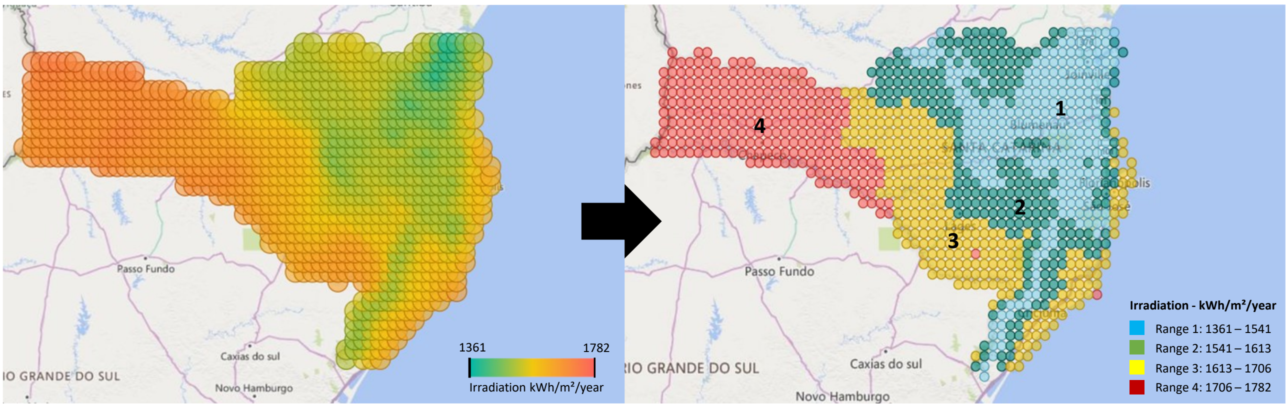


Figure 2.13. Map of the annual average daily latitude-tilted (GTI) and annual average daily GTI divided in four ranges (quartiles) for the Santa Catarina state in South Brazil.

The results show that, by dividing the state territory by irradiation ranges using statistical quartiles, it was possible to identify more clearly how the different levels of latitude-tilted irradiation are distributed throughout the analyzed region.

Figure 2.14 shows the location of 570 out of the 1250 identical 2.65 kWp residential rooftop PV generators (filtered by the technical-statistical algorithm presented) scattered over the state of Santa Catarina territory on the left, and the average daily GTI grid (on an annual basis) divided by irradiation ranges on the right.

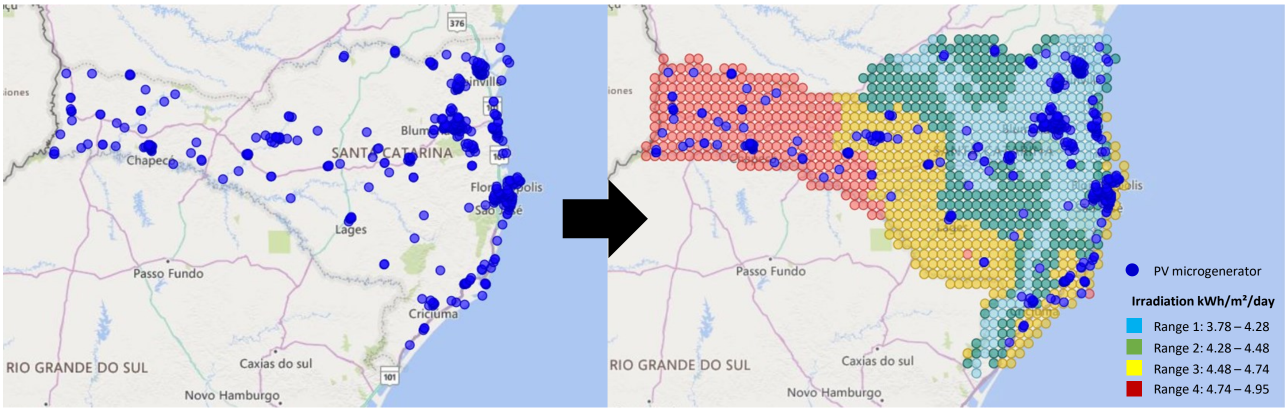


Figure 2.14. Location of 570 out of the 1250 identical 2.65 kWp residential rooftop PV generators (blue dots) in Santa Catarina and within the GTI dot grid (satellite data) divided by irradiation ranges (annual basis).

The results show the location of the PV generators in each annual latitude-tilted irradiation quartile after the application of the technical-statistical filters used to guarantee the quality and significance of the measured data, according to the methodology presented in the technical-statistical algorithm. To evaluate the seasonality of the measured energy yield of the ensemble located in the four ranges, the monthly evolution of the average daily yield of each of them was evaluated.

Figure 2.15 shows, for the 12 months of 2019 and for the four ranges of tilted solar irradiation (quartiles), the monthly evolution of the distribution curves of the measured yields, the average daily yields and the variability of the yield of the PV generator ensembles.

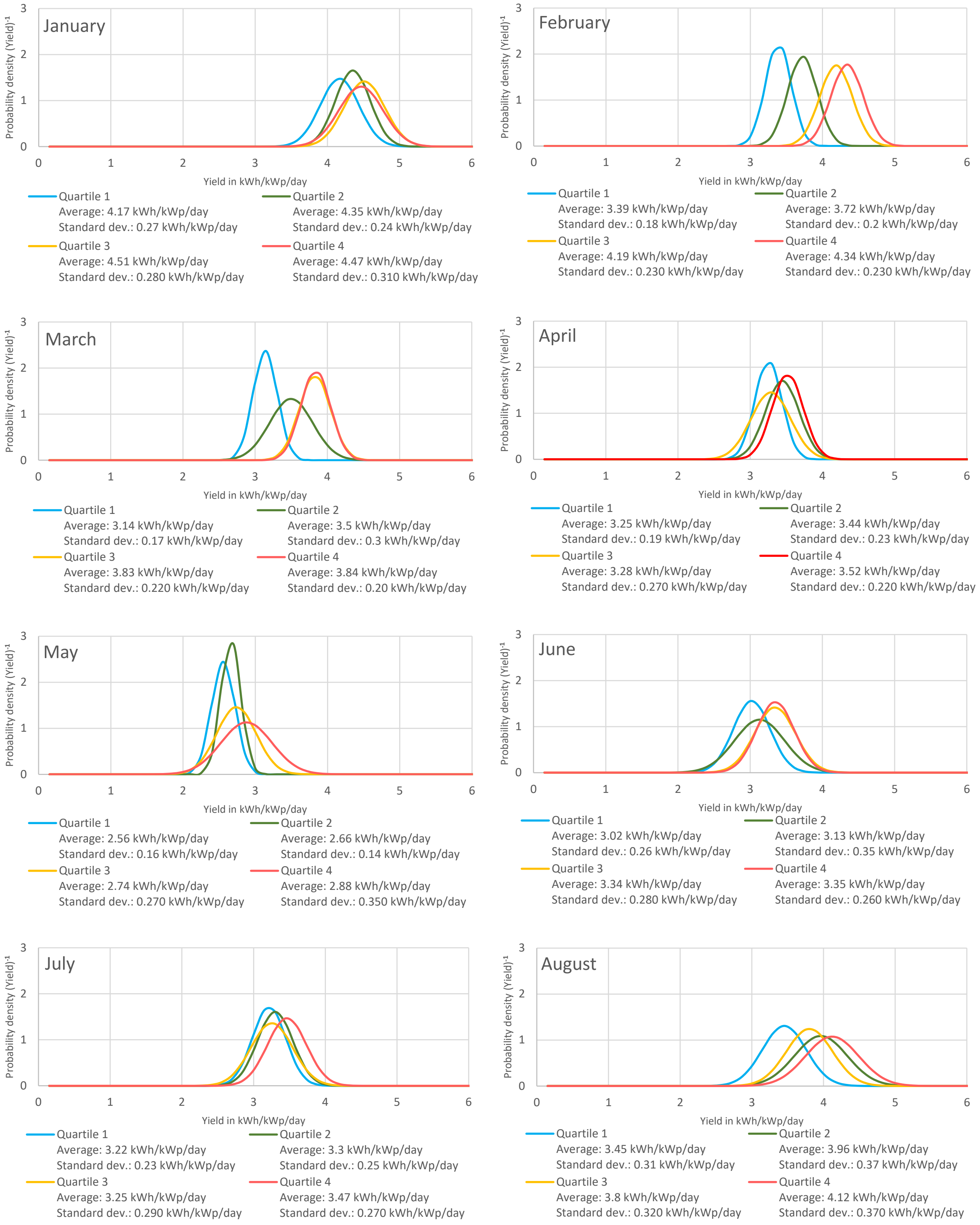


Figure 2.15. Monthly evolution of the distribution curves of measured daily average energy yield (in kWh/kWp/day) of the PV generators ensemble distributed in the four quartiles described and shown in Figures 2.4 and 2.5.

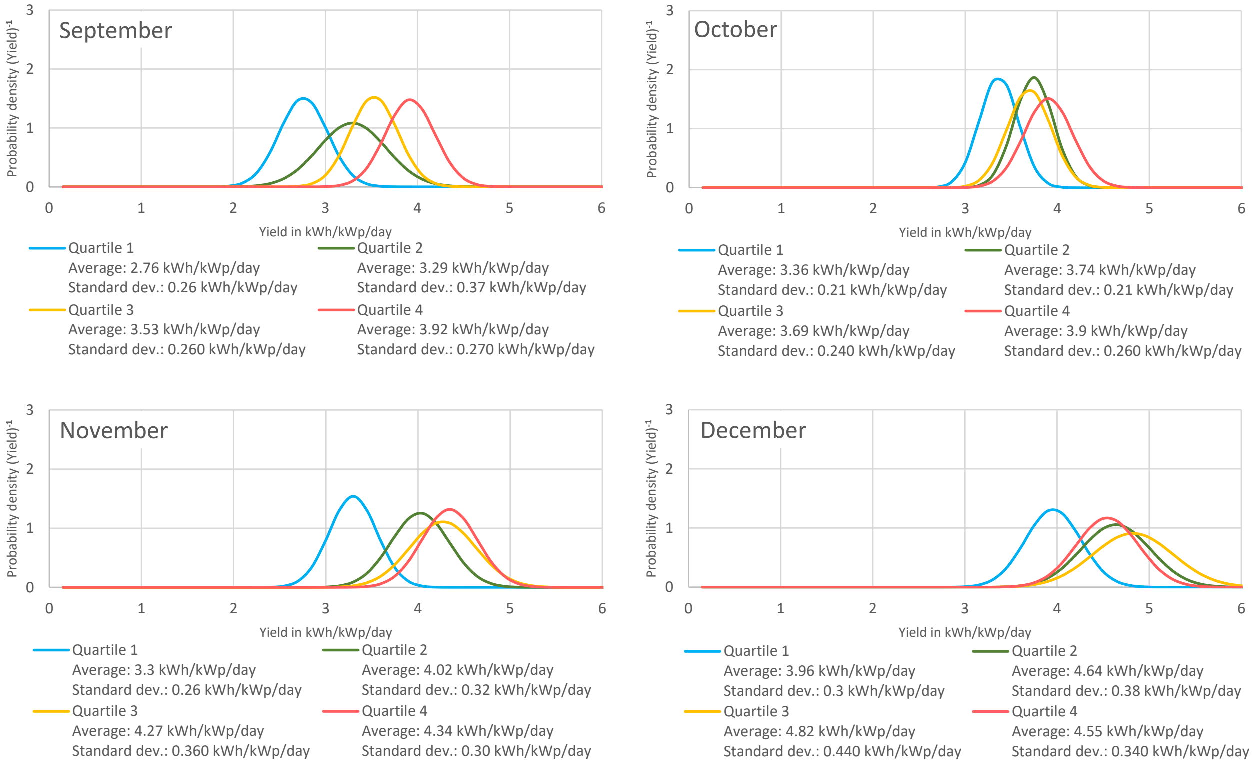


Figure 2.15. Monthly evolution of the distribution curves of measured daily average energy yield (in kWh/kWp/day) of the PV generators ensemble distributed in the four quartiles described and shown in Figures 2.4 and 2.5.

For the summer months of 2019 (Jan to Mar), the results show for Range 1 an average yield between 3.14 and 4.17 kWh/kWp/day, for Range 2 between 3.5 and 4.35 kWh /kWp/day, for Range 3 between 4.51 and 3.83 kWh/kWp/day, and for Range 4 between 3.84 and 4.47 kWh/kWp/day.

For the autumn months of 2019 (Apr to Jun), the results show for Range 1 average yield between 2.56 and 3.25 kWh/kWp/day, for Range 2 between 2.66 and 3.44 kWh/ kWp/day, for Range 3 between 2.74 and 3.34 kWh/kWp/day, and for Range 4 between 2.88 and 3.52 kWh/kWp/day.

For the winter months of 2019 (July to Sept), the results show for Range 1 average Yield between 2.76 and 3.45 kWh/kWp/day, for Range 2 between 3.29 and 3.96 kWh/ kWp/day, for Range 3 between 3.25 and 3.8 kWh/kWp/day, and for Range 4 between 3.47 and 4.12 kWh/kWp/day.

For the spring months of 2019 (Oct to Dec), the results show for Range 1 average yield between 3.3 and 3.96 kWh/kWp/day, for Range 2 between 3.74 and 4.64 kWh/ kWp/day, for Range 3 between 3.69 and 4.82 kWh/kWp/day, and for Range 4 between 3.9 and 4.55 kWh/kWp/day.

It can be observed that, in all 12 months and for all ranges of latitude-tilted irradiation (1st to 4th quartile), after the application of the technical-statistical filters, all the distribution curves are equivalent to a statistically normal distribution. When looking at the histograms for the year 2019, the curves of each irradiation range are similar in the months of January and July. This phenomenon occurs because in these months the cloud cover behavior throughout the entire territory of Santa Catarina is similar. As for the other months, the curves differ significantly due to the regional variations in cloud cover existing in the region. Figure 2.16 shows the distribution curves of the average daily measured energy yield for the year 2019.

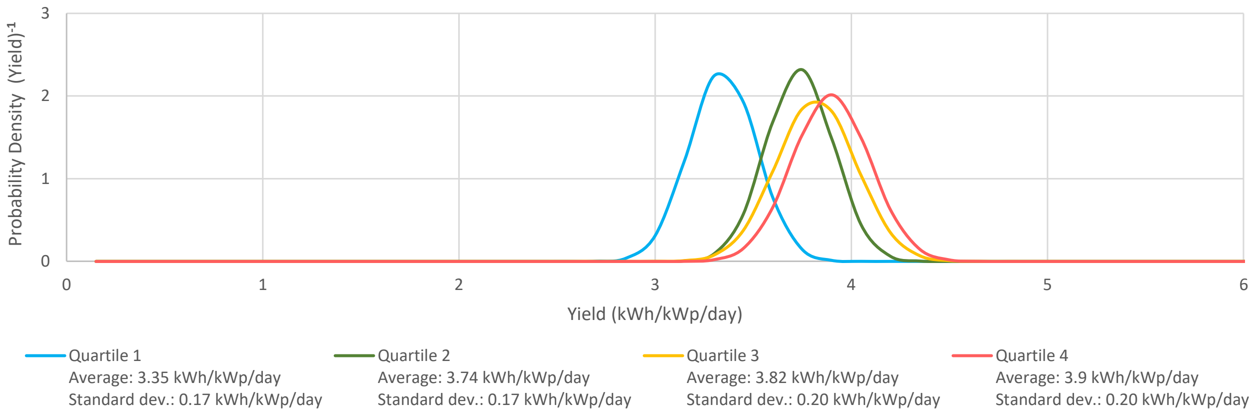


Figure 2.16. Distribution curves of measured daily average yields. Base year: 2019.

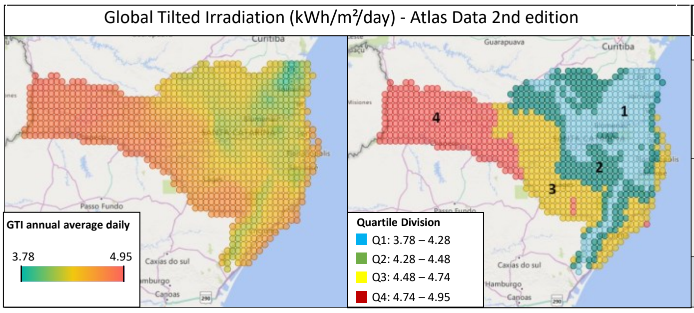
It was observed that after the application of the technical-statistical filters, the annual distribution curves of the average daily energy yield correspond to the normal distribution curve for all the four statistical quartiles of latitude-tilted irradiation. The results show that the average PV generators daily energy yield varies between 3.35 kWh/kWp/day (Range 1) to 3.90 kWh/kWp/day (Range 4). It also shows that the four latitude-tilted irradiation ranges analyzed show similar variability in energy yield data.

The results show that the adoption of both filters (technical and statistical), allows defective PV systems and PV systems with non-representative generation data to be excluded from the analyzed sample, dispensing with data processing via gap-filling and the use of ground meteorological data measurement stations next to the PV generator.

The technical quality of the generation data of each analyzed PV system was guaranteed through the adoption of technical filters, as described in the method. The representativeness of the PV generation data was obtained through the statistical algorithm, presented in the method, whose objective was to identify outliers, thus providing a normal distribution for the Yield of the sample, as provided for in the literature.

2.3.5 Information View: Solar PV Energy Yield Map

Figure 2.17 shows, the annual GTI maps, the GTI maps divided by irradiation ranges (quartiles) and, for the 2019 base year, the energy yield statistical information for each sample of PV generator ensembles. For each range (Quartile) of the tilted irradiation, the number of elements that make up the sample, the mean, median, maximum, and minimum values of the measured yield, the error margins for 95% reliability and the confirmation of the normality tests QQ-plot are presented (R^2). Additionally, estimated theoretical Yield values are presented considering PR = 80%.



Global Tilted Irradiation (kWh/m²/day) - Atlas Data 2nd edition

Yield statistical information of microgenerator samples

Base Year: 2019	Quatile 1	Quatile 2	Quatile 3	Quatile 4
Nº of elements	238	105	143	84
$\overline{X}$ Measured yield (kWh/kWp/day)	3.35	3.74	3.82	3.90
± margin of error with 95% reliability (%)	0.65%	0.88%	0.87%	1.09%
QQ-plot normality test (R^2)	99.4%	98.8%	99.4%	98.6%
Median Yield measured (kWh/kWp/day)	3.36	3.75	3.83	3.91
Minimum yield (kWh/kWp/day)	2.87	3.22	3.27	3.41
Maximum yield (kWh/kWp/day)	3.82	4.26	4.38	4.37
$\overline{X}$ Theoretical yield (PR 80%) (kWh/kWp)	3.4	3.5	3.7	3.9
Δ% $\overline{X}$ Yield (Theoretical x Measured)	0.3%	7.2%	3.7%	0.7%

Figure 2.17. Annual GTI map, GTI division by quartiles and energy yield statistical information of the PV generators ensemble (Year 2019).

The results show, for each statistical quartile analyzed (Ranges), with 95% reliability, the average daily energy yield.

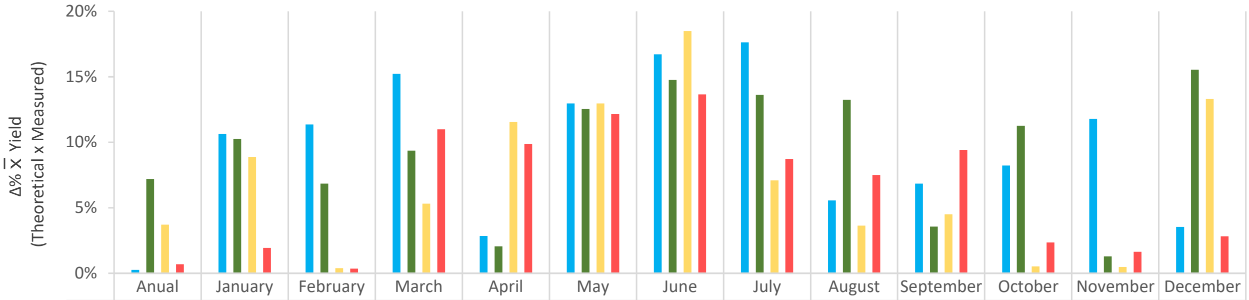
In Range 1, for annual global latitude tilt solar irradiation (GTI) varying between 3.78 and 4.28 kWh/m²/day (1380 to 1560 kWh/m²/year), the average daily PV yield was 3.35 kWh/kWp/day (equivalent to 1223 kWh/kWp/year), and margin of error of 0.65%.

In Range 2, for annual GTI varying between 4.28 and 4.48 kWh/m². day (1560 and 1635 kWh/m²/year), the average daily Yield was 3.74 kWh/kWp/day (equivalent to 1365 kWh/kWp/year), and margin of error of 0.88%.

In Range 3, for annual GTI varying between 4.48 and 4.74 kWh/m²/day (1635 and 1730 kWh/m²/year), the average daily yield was 3.82 kWh/kWp/day (equivalent to 1395 kWh/kWp/year), and margin of error of 0.87%.

In Range 4, for annual GTI varying between 4.74 and 4.95 kWh/m²/day (1730 and 1800 kWh/m²/year), the average daily yield was 3.90 kWh/kWp/day (1423 kWh/kWp/year), and margin of error of 1.09%.

Figure 2.18 shows, for the 4 GTI ranges, in percentage values, the differences between the measured average values and the theoretical average values (for a predefined PR = 0.8).



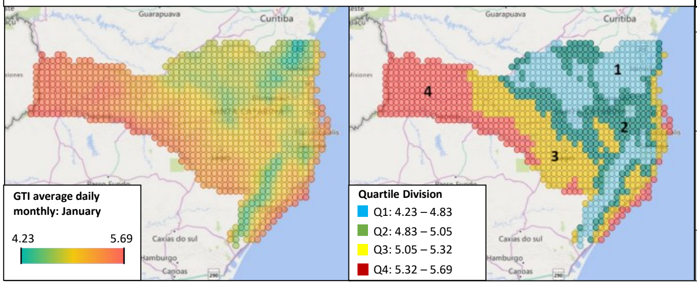
	Anual	January	February	March	April	May	June	July	August	September	October	November	December
🟦 Q1	0.3%	10.6%	11.4%	15.2%	2.9%	13.0%	16.7%	17.6%	5.6%	6.8%	8.2%	11.8%	3.5%
🟩 Q2	7.2%	10.3%	6.8%	9.4%	2.1%	12.5%	14.8%	13.6%	13.2%	3.6%	11.3%	1.3%	15.5%
🟨 Q3	3.7%	8.9%	0.4%	5.3%	11.5%	13.0%	18.5%	7.1%	3.6%	4.5%	0.5%	0.5%	13.3%
🟥 Q4	0.7%	1.9%	0.4%	11.0%	9.9%	12.1%	13.7%	8.7%	7.5%	9.4%	2.4%	1.6%	2.8%

Figure 2.18. Percentage differences between the averages of measured energy yield and theoretical energy yield.

The results show annual differences between the average measured energy yield values and the theoretical average yield values of 0.3% (Range 1), 7.2% (Range 2), 3.7% (Range 3) and 0.7% (Range 4).

Figures 2.19 to 2.30 show, for the period between January and December 2019, the GTI maps, the GTI maps divided by irradiation ranges (quartiles) and energy yield statistical information for each sample of PV generator ensembles. Normality tests QQ-plot (R^2) are presented for each month and for each range of latitude-tilted irradiation, as well as the number of elements that make up the sample, the average, the median and the maximum and minimum values of the measured energy yield, and the error margins for 95% reliability and confirmation. Additionally, estimated theoretical energy yield values are presented (for a predefined PR = 80%).

Global Tilted Irradiation (kWh/m²/day) - Atlas Data 2nd edition

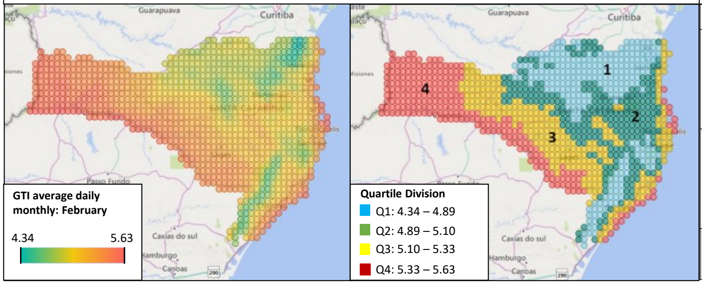


Yield statistical information of microgenerator samples

January 2019	Q 1	Q2	Q 3	Q 4
Nº of elements	223	290	335	164
$\overline{X}$ Measured yield (kWh/kWp/day)	4.17	4.35	4.51	4.47
± margin of error with 95% reliability (%)	0.85%	0.64%	0.67%	1.05%
QQ-plot normality test (R^2)	98.7%	98.8%	98.8%	99.1%
Median Yield measured (kWh/kWp/day)	4.21	4.37	4.53	4.44
Minimum yield (kWh/kWp/day)	3.43	3.70	3.84	3.60
Maximum yield (kWh/kWp/day)	4.94	5.04	5.18	5.35
$\overline{X}$ Theoretical yield (PR 80%) (kWh/kWp)	3.8	3.9	4.1	4.4
Δ% $\overline{X}$ Yield (Theoretical x Measured)	10.6%	10.3%	8.9%	1.9%

Figure 2.19. GTI map, GTI division by quartiles and energy yield statistical information of the PV generators ensemble (Jan 2019).

Global Tilted Irradiation (kWh/m²/day) - Atlas Data 2nd edition

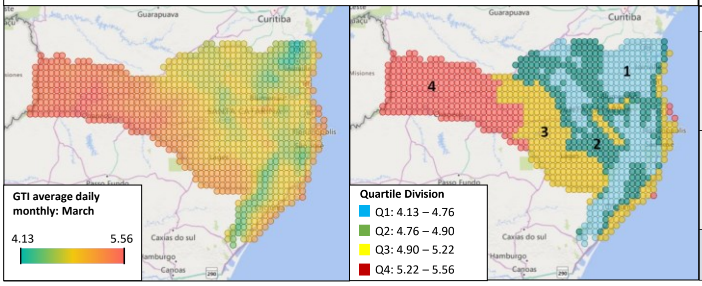


Yield statistical information of microgenerator samples

February 2019	Q 1	Q2	Q 3	Q 4
Nº of elements	219	274	330	155
$\overline{X}$ Measured yield (kWh/kWp/day)	3.39	3.72	4.19	4.34
± margin of error with 95% reliability (%)	0.70%	0.65%	0.05%	0.82%
QQ-plot normality test (R²)	99.4%	99.4%	98.6%	96.1%
Median Yield measured (kWh/kWp/day)	3.40	3.70	4.21	4.36
Minimum yield (kWh/kWp/day)	2.92	3.20	3.57	3.77
Maximum yield (kWh/kWp/day)	3.86	4.25	4.82	4.96
$\overline{X}$ Theoretical yield (PR 80%) (kWh/kWp)	3.8	4.0	4.2	4.4
Δ% $\overline{X}$ Yield (Theoretical x Measured)	11.4%	6.8%	0.4%	0.4%

Figure 2.20. GTI map, GTI division by quartiles and energy yield statistical information of the PV generators ensemble (Feb 2019).

Global Tilted Irradiation (kWh/m²/day) - Atlas Data 2nd edition

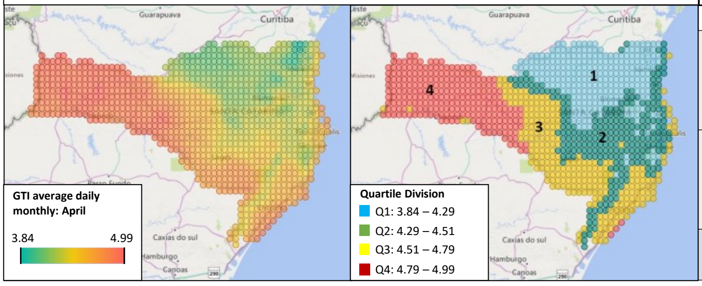


Yield statistical information of microgenerator samples

March 2019	Q 1	Q2	Q 3	Q 4
Nº of elements	250	327	249	145
$\overline{X}$ Measured yield (kWh/kWp/day)	3.14	3.50	3.83	3.84
± margin of error with 95% reliability (%)	0.66%	0.93%	0.70%	0.87%
QQ-plot normality test (R²)	99.5%	98.3%	98.2%	99.1%
Median Yield measured (kWh/kWp/day)	3.15	3.47	3.87	3.84
Minimum yield (kWh/kWp/day)	2.68	2.72	3.23	3.27
Maximum yield (kWh/kWp/day)	3.59	4.30	4.41	4.40
$\overline{X}$ Theoretical yield (PR 80%) (kWh/kWp)	3.7	3.9	4.0	4.3
Δ% $\overline{X}$ Yield (Theoretical x Measured)	15.2%	9.4%	5.3%	11.0%

Figure 2.21. GTI map, GTI division by quartiles and energy yield statistical information of the PV generators ensemble (Mar 2019).

Global Tilted Irradiation (kWh/m²/day) - Atlas Data 2nd edition

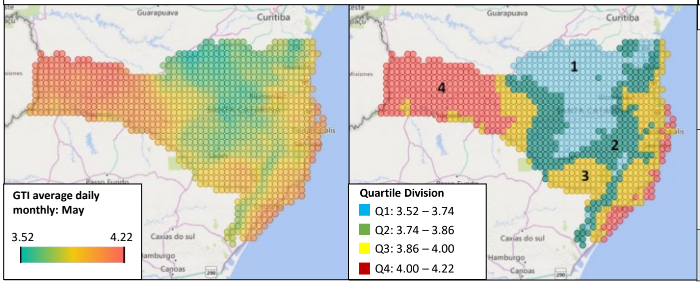


Yield statistical information of microgenerator samples

April 2019	Q 1	Q2	Q 3	Q 4
Nº of elements	240	431	149	143
$\overline{X}$ Measured yield (kWh/kWp/day)	3.25	3.44	3.28	3.52
± margin of error with 95% reliability (%)	0.72%	0.64%	1.34%	1.00%
QQ-plot normality test (R²)	99.3%	99.2%	99.1%	98.8%
Median Yield measured (kWh/kWp/day)	3.26	3.43	3.27	3.52
Minimum yield (kWh/kWp/day)	2.74	2.82	2.59	2.99
Maximum yield (kWh/kWp/day)	3.78	4.09	3.97	4.07
$\overline{X}$ Theoretical yield (PR 80%) (kWh/kWp)	3.3	3.5	3.7	3.9
Δ% $\overline{X}$ Yield (Theoretical x Measured)	2.9%	2.1%	11.5%	9.9%

Figure 2.22. GTI map, GTI division by quartiles and energy yield statistical information of the PV generators ensemble (Apr 2019).

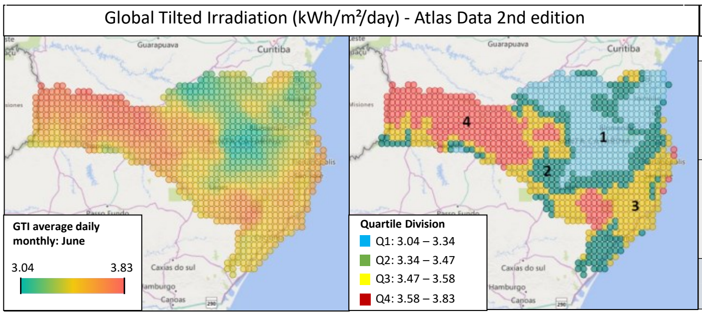
Global Tilted Irradiation (kWh/m²/day) - Atlas Data 2nd edition



Yield statistical information of microgenerator samples

May 2019	Q 1	Q2	Q 3	Q 4
Nº of elements	175	113	441	226
$\overline{X}$ Measured yield (kWh/kWp/day)	2.56	2.66	2.74	2.88
± margin of error with 95% reliability (%)	0.95%	0.94%	0.93%	1.60%
QQ-plot normality test (R²)	99.0%	98.6%	99.1%	99.5%
Median Yield measured (kWh/kWp/day)	2.57	2.67	2.71	2.89
Minimum yield (kWh/kWp/day)	2.12	2.31	2.03	1.94
Maximum yield (kWh/kWp/day)	3.00	3.01	3.46	3.84
$\overline{X}$ Theoretical yield (PR 80%) (kWh/kWp)	2.9	3.0	3.1	3.3
Δ% $\overline{X}$ Yield (Theoretical x Measured)	13.0%	12.5%	13.0%	12.1%

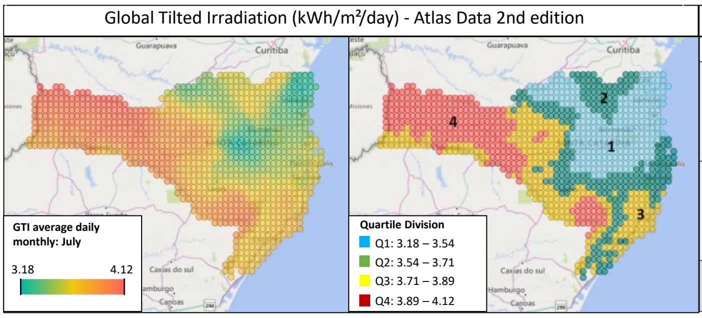
Figure 2.23. GTI map, GTI division by quartiles and energy yield statistical information of the PV generators ensemble (May 2019).



Yield statistical information of microgenerator samples

June 2019	Q 1	Q2	Q 3	Q 4
Nº of elements	342	157	324	104
$\overline{X}$ Measured yield (kWh/kWp/day)	3.02	3.13	3.34	3.35
± margin of error with 95% reliability (%)	0.90%	1.73%	0.92%	1.49%
QQ-plot normality test (R²)	99.1%	99.1%	99.4%	99.1%
Median Yield measured (kWh/kWp/day)	3.03	3.16	3.36	3.35
Minimum yield (kWh/kWp/day)	2.30	2.25	2.59	2.65
Maximum yield (kWh/kWp/day)	3.75	3.99	4.11	4.02
$\overline{X}$ Theoretical yield (PR 80%) (kWh/kWp)	2.6	2.7	2.8	2.9
Δ% $\overline{X}$ Yield (Theoretical x Measured)	16.7%	14.8%	18.5%	13.7%

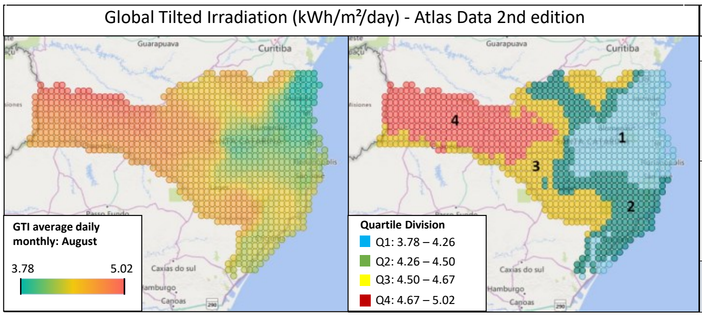
Figure 2.24. GTI map, GTI division by quartiles and energy yield statistical information of the PV generators ensemble (Jun 2019).



Yield statistical information of microgenerator samples

July 2019	Q 1	Q2	Q 3	Q 4
Nº of elements	403	224	133	130
$\overline{X}$ Measured yield (kWh/kWp/day)	3.22	3.30	3.25	3.47
± margin of error with 95% reliability (%)	0.71%	0.98%	1.53%	1.35%
QQ-plot normality test (R²)	99.7%	99.4%	99.4%	99.5%
Median Yield measured (kWh/kWp/day)	3.23	3.31	3.27	3.47
Minimum yield (kWh/kWp/day)	2.56	2.67	2.43	2.76
Maximum yield (kWh/kWp/day)	3.87	3.94	4.07	4.18
$\overline{X}$ Theoretical yield (PR 80%) (kWh/kWp)	2.7	2.9	3.0	3.2
Δ% $\overline{X}$ Yield (Theoretical x Measured)	17.6%	13.6%	7.1%	8.7%

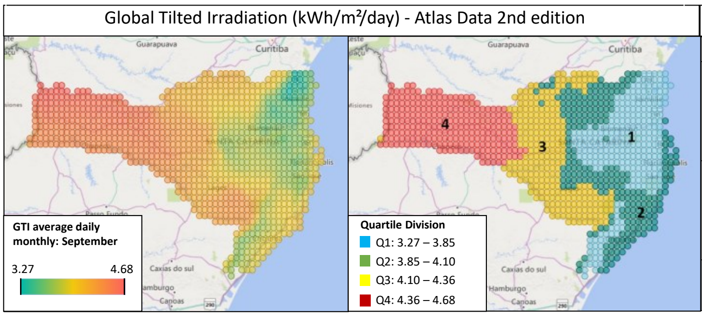
Figure 2.25. GTI map, GTI division by quartiles and energy yield statistical information of the PV generators ensemble (Jul 2019).



Yield statistical information of microgenerator samples

August 2019	Q 1	Q2	Q 3	Q 4
Nº of elements	604	111	37	156
$\overline{X}$ Measured yield (kWh/kWp/day)	3.45	3.96	3.80	4.12
± margin of error with 95% reliability (%)	0.70%	1.72%	2.72%	1.41%
QQ-plot normality test (R²)	99.7%	98.8%	98.5%	98.8%
Median Yield measured (kWh/kWp/day)	3.44	3.98	3.78	4.13
Minimum yield (kWh/kWp/day)	2.63	2.92	2.77	3.14
Maximum yield (kWh/kWp/day)	4.28	5.02	4.81	5.09
$\overline{X}$ Theoretical yield (PR 80%) (kWh/kWp)	3.3	3.5	3.7	3.8
Δ% $\overline{X}$ Yield (Theoretical x Measured)	5.6%	13.2%	3.6%	7.5%

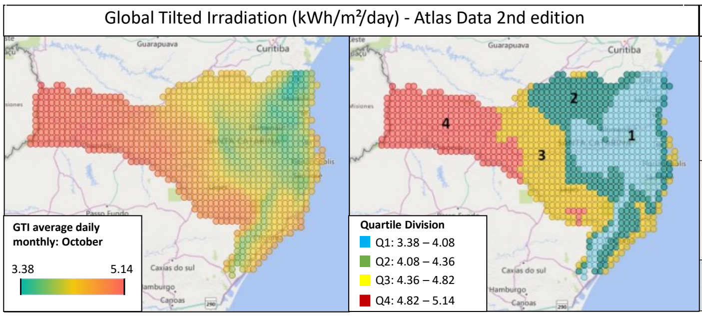
Figure 2.26. GTI map, GTI division by quartiles and energy yield statistical information of the PV generators ensemble (Aug 2019).



Yield statistical information of microgenerator samples

September 2019	Q 1	Q2	Q 3	Q 4
Nº of elements	446	242	44	136
$\overline{X}$ Measured yield (kWh/kWp/day)	2.76	3.29	3.53	3.92
± margin of error with 95% reliability (%)	0.87%	1.41%	2.18%	1.15%
QQ-plot normality test (R²)	99.5%	95.5%	98.2%	99.5%
Median Yield measured (kWh/kWp/day)	2.78	3.19	3.54	3.92
Minimum yield (kWh/kWp/day)	2.02	2.34	2.82	3.18
Maximum yield (kWh/kWp/day)	3.46	4.23	4.28	4.66
$\overline{X}$ Theoretical yield (PR 80%) (kWh/kWp)	3.0	3.2	3.4	3.6
Δ% $\overline{X}$ Yield (Theoretical x Measured)	6.8%	3.6%	4.5%	9.4%

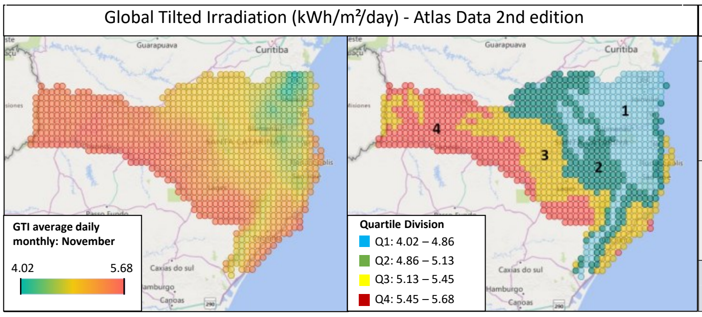
Figure 2.27. GTI map, GTI division by quartiles and energy yield statistical information of the PV generators ensemble (Sep 2019).



Yield statistical information of microgenerator samples

October 2019	Q 1	Q2	Q 3	Q 4
Nº of elements	320	196	71	106
$\overline{X}$ Measured yield (kWh/kWp/day)	3.36	3.76	3.69	3.90
± margin of error with 95% reliability (%)	0.69%	0.87%	1.51%	1.29%
QQ-plot normality test (R²)	99.1%	99.1%	98.3%	99.1%
Median Yield measured (kWh/kWp/day)	3.37	3.78	3.71	3.91
Minimum yield (kWh/kWp/day)	2.84	3.11	3.07	3.15
Maximum yield (kWh/kWp/day)	3.88	4.40	4.31	4.66
$\overline{X}$ Theoretical yield (PR 80%) (kWh/kWp)	3.1	3.4	3.7	4.0
Δ% $\overline{X}$ Yield (Theoretical x Measured)	8.2%	11.3%	0.5%	2.4%

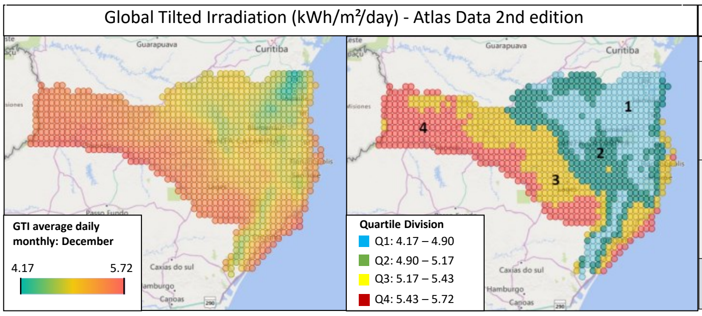
Figure 2.28. GTI map, GTI division by quartiles and energy yield statistical information of the PV generators ensemble (Oct 2019).



Yield statistical information of microgenerator samples

November 2019	Q 1	Q2	Q 3	Q 4
Nº of elements	327	201	166	118
$\overline{X}$ Measured yield (kWh/kWp/day)	3.30	4.02	4.27	4.34
± margin of error with 95% reliability (%)	0.85%	1.09%	1.28%	1.26%
QQ-plot normality test (R²)	99.6%	99.0%	99.3%	98.2%
Median Yield measured (kWh/kWp/day)	3.32	4.06	4.27	4.31
Minimum yield (kWh/kWp/day)	2.61	3.09	3.33	3.62
Maximum yield (kWh/kWp/day)	3.98	4.98	5.25	5.06
$\overline{X}$ Theoretical yield (PR 80%) (kWh/kWp)	3.7	4.0	4.3	4.4
Δ% $\overline{X}$ Yield (Theoretical x Measured)	11.8%	1.3%	0.5%	1.6%

Figure 2.29. GTI map, GTI division by quartiles and energy yield statistical information of the PV generators ensemble (Nov 2019).



Yield statistical information of microgenerator samples

December 2019	Q 1	Q2	Q 3	Q 4
Nº of elements	302	142	228	103
$\overline{X}$ Measured yield (kWh/kWp/day)	3.96	4.64	4.82	4.55
± margin of error with 95% reliability (%)	0.86%	1.34%	1.18%	1.44%
QQ-plot normality test (R²)	97.8%	98.1%	99.1%	98.6%
Median Yield measured (kWh/kWp/day)	4.01	4.64	4.87	4.51
Minimum yield (kWh/kWp/day)	3.11	3.64	3.60	3.66
Maximum yield (kWh/kWp/day)	4.81	5.71	6.04	5.45
$\overline{X}$ Theoretical yield (PR 80%) (kWh/kWp)	3.8	4.0	4.3	4.4
Δ% $\overline{X}$ Yield (Theoretical x Measured)	3.5%	15.5%	13.3%	2.8%

Figure 2.30. GTI map, GTI division by quartiles and energy yield statistical information of the PV generators ensemble (Dec 2019).

The results clearly show the seasonality of latitude-tilted solar irradiation and consequently the energy yield of PV generators. Figures 2.19 to 2.30 allow for the analysis of PV generators monthly energy yields for different regions in a simple and intuitive way. To be able to predict the approximate monthly electricity generation of any PV generator, one simply must identify its position in one of the four ranges in the monthly latitude-tilted irradiation maps, multiply the PV system nominal power by the average daily energy yield of the corresponding range (quartile), and multiply by the number of days of the month. In this way, it is possible to predict, with 95% confidence, the monthly generation of future PV rooftops to be installed in the region.

PV technology evolution is increasingly pushing PV module efficiencies over the 20% mark, and 30% efficiencies are expected for tandem PV modules by the end of the current decade. It is important to emphasize that these results are in principle not likely to be dependent on the evolution of the PV technology, which is basically improving energy conversion efficiency, which translates itself in an evolution in power/area (W/m^2). Energy yield is measured in kWh or energy produced by installed power, measured in kWp over time, and is thus irrespective of conversion efficiency. Technology evolution is resulting in more power per surface area, and not necessarily in more energy per installed power, which makes our electricity generation expectations valid in the longer run. The variation in average ambient temperature, and solar irradiation arising from generalized changes in weather patterns are also of too small a magnitude to affect these results. Changes in weather patterns including rising temperatures will play only a minor role in the overall PV performance, as temperature coefficients on power are smaller than 0.5%/ degree C.

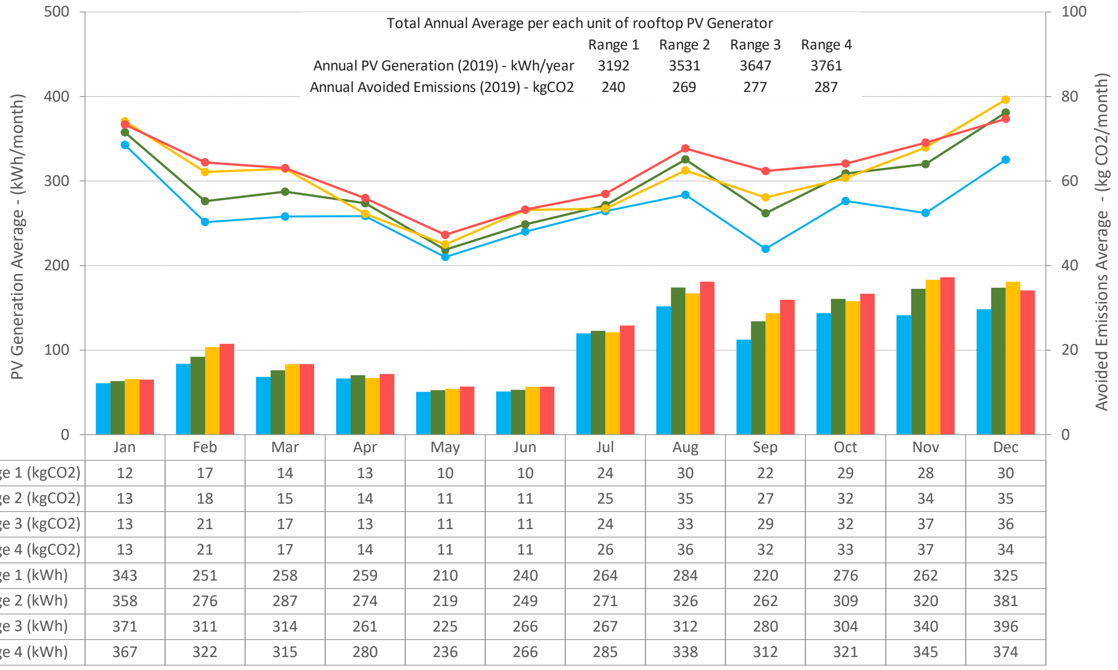
What the consumer ultimately buys is energy generation (kWh), which is basically dependent on PV module power (kW, and not on efficiency) integrated over time, and this energy yield (kWh/kWp over time) is basically not changing with technology evolution. The interannual variability of the solar radiation resource availability in Brazil ranged from 4.5% to 5.5% over a 17 years period, which includes a complete solar cycle (PEREIRA et al., 2017), and which was taken into account in our 95% confidence level. The methodology proposed here can easily be extended to any location, and the case study presented here illustrates the application and benefits of the method.

From a sustainability perspective and considering the high reliance of the Brazilian energy mix on hydropower plants, climate change is resulting in more water constrains for electricity generation, highlighting the benefits of a more widespread adoption of benign and renewable energy technologies such as solar photovoltaics.

2.3.6 Impacts on CO_2 emissions from the uptake of PV generation per rooftop unit

The growth of distributed PV generation in Brazil over the years is seen as a strong ally of a sustainable development, as it is an easily accessible and affordable alternative to replace the use of fossil fuels.

PV generation results presented here allowed to identify the average avoided CO_2 of a representative PV rooftop for four different regions (Ranges) of the state of Santa Catarina. Figure 2.31 presents the monthly evolution of avoided CO_2 emissions in contrast to the PV generation of 1250 PV rooftops ensemble average.



Total Annual Average per each unit of rooftop PV Generator

	Range 1	Range 2	Range 3	Range 4
Annual PV Generation (2019) - kWh/year	3192	3531	3647	3761
Annual Avoided Emissions (2019) - kgCO2	240	269	277	287

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Range 1 (kgCO2)	12	17	14	13	10	10	24	30	22	29	28	30
Range 2 (kgCO2)	13	18	15	14	11	11	25	35	27	32	34	35
Range 3 (kgCO2)	13	21	17	13	11	11	24	33	29	32	37	36
Range 4 (kgCO2)	13	21	17	14	11	11	26	36	32	33	37	34
Range 1 (kWh)	343	251	258	259	210	240	264	284	220	276	262	325
Range 2 (kWh)	358	276	287	274	219	249	271	326	262	309	320	381
Range 3 (kWh)	371	311	314	261	225	266	267	312	280	304	340	396
Range 4 (kWh)	367	322	315	280	236	266	285	338	312	321	345	374

Figure 2.31. Monthly evolution of avoided CO_2 emissions in contrast to the PV generation of the 1250 rooftop PV ensemble.

The results of Figure 2.31 show the total annual CO_2 avoided for each 2.65 kWp PV rooftop analyzed.

The annual average PV generation of each PV rooftop analyzed was around to 3,353 kWh/year, which corresponds to an avoided CO_2 emission of 268.25 $kgCO_2$/year. For all the 1250 PV rooftops ensemble, the average avoided CO_2 emission was around to 335.30 tCO_2/year. Considering all 1250 PV systems within the area with the lowest PV generation potential (Range 1), the ensemble would annually avoid around to 300 tCO_2 emissions. For the area with the biggest PV generation potential (Range 4), the ensemble would annually avoid around to 358.75 tCO_2 emissions.

2.4 Conclusions

Although the method developed has a general character, this research focused on developing a methodology for the energy yield assessment of a large ensemble of residential rooftop PV generators, and on its application in a case study in the state of Santa Catarina in the South of Brazil. To this end, the exploration and strategic analysis of data was done through BI concepts combined with a technical-statistical algorithm to evaluate the energy yield of PV generators. The energy yield of an ensemble of 1250 identical distributed PV systems, with an individual rated power of 2.65 kWp, and a total installed power around to 3.3 MWp was evaluated.

The technical-statistical algorithm was used to carry out an energy yield assessment of a solar PV rooftop ensemble. In the analyzed period, there was a gradual increase in the number of PV generators which had to be removed from the dataset by defined technical filters. During the 12 months of the year, more than half of the PV generators ensemble (52.1% or 651 units) presented at least one month with problems in the generation data. Of the 1,250 identical PV roofs analyzed, only 598 units passed the technical filters. The methodology proposed, and the results obtained from this case study clearly showed the lack of adequate maintenance of the dispersed PV generators.

The application of the statistical filter after the application of technical filters in most groups of samples removed less than 10% of outliers. In general, it was necessary to apply two cycles of the statistical filter until there was no more discrepancy in the data. To evaluate the energy yield of the PV microgenerators, a sample composed of 570 systems remained.

For the case study, the results show, with 95% reliability, an average daily energy yield of 3.35 kWh/kWp/day with a margin of error of 0.65% (annual GTI varying between 3.78 and 4.28 kWh/m²/day), 3.74 kWh/kWp/day with a margin of error of 0,88% (annual GTI varying between 4.28 and 4.48 kWh/m²/day), 3.82 kWh/kWp/day with an error margin of 0.87% (annual GTI varying between 4.48 and 4.74 kWh/m²/day) and 3.90 kWh/kWp/day with a margin of error of 1.09% (annual GTI varying between 4.74 and 4.95 kWh/m²/day).

The annual average PV generation of each PV rooftop analyzed is around to 3,353 kWh/year, which corresponds to an avoided CO_2 emission of 268.25 $kgCO_2$/year. For all the 1250 PV rooftops ensemble, the average avoided CO_2 emission is around to 335.30 tCO_2/year.

The results were presented visually on maps via GIS and through statistical indicators, such as average daily energy yield, data variability, maximum and minimum values, margins of error for 95% reliability, among others. The quality and significance of the data was guaranteed by the technical-statistical algorithm adopted.

The Energy Business Intelligence E-BI tool facilitated the understanding of the flow of information related to hundreds of PV generators and can be extended to any sample size. It was possible, through the dashboards developed, to immediately visualize the PV solar potential throughout the territory analyzed, based on information from the solar resource available from satellite data, and the measured PV generation from each PV system. The results obtained in this research can be used to predict with 95% reliability, the monthly/annual generation of future PV systems to be installed in Santa Catarina, and the same methodology can be applied mutatis mutandis to produce analogous results anywhere.

The novelty of this research is the development of an algorithm capable of technically evaluating a large sample of PV systems connected to the electrical grid, which, due to the rigid technical filters developed, resulted in the exemption to use gap-filling techniques, as well as validating statistically the compliance of the measured data. Furthermore, the method uses BI concepts to structure and manage the information at dashboards with predefined indicators. The method of data management and information developed using the concepts of BI, allows the application of a tool with a language already known by many managers to remotely assist in the decision-making of companies responsible for the management of ensembles PV systems connected to the electrical grid.

Currently, small energy producers are the main responsible for the capillarity and dissemination of distributed PV generation in Brazil and elsewhere. This growing market is still recent and has a lot to evolve. The distributed PV generation data management is not yet completely dominated by electricity utilities, and tools and methods such as the ones presented in this work are designed to assist in this task.

3 THE ROLE AND BENEFITS OF RESIDENTIAL ROOFTOP PHOTOVOLTAIC PROSUMERS IN BRAZIL

This chapter is the transcription of the following paper:

The role and benefits of residential rooftop photovoltaic prosumers in Brazil.

Authored by: Andrigo Filippo Antoniolli, Helena Flávia Naspolini, João Frederico de Abreu and Ricardo Rüther.

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Abstract

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

Keywords: Energy efficiency, Prosumer, Photovoltaics, Distributed generation.

3.1 Introduction

Technological advances and the desire for decarbonization are factors that have been transforming the energy sector worldwide, changing the traditional means of electricity generation and consumption. The residential sector contributes to a very dynamic and evolutionary scenario, due to the use of more efficient electrical appliances, the uptake of electromobility with home charging and the possibility of vehicle-to-home (V2H) and vehicle-to-grid (V2G), as well as the integration of self-generation with photovoltaic (PV) systems and batteries, which impact the generation, transmission, and distribution of electricity. (ENONGENE et al., 2019; FISCHER; SURMANN; BYSKOV, 2020; GAGLIA et al., 2019; HAN et al., 2020; MORILL; ROSAS-FLORES; ZEN, 2019).

Buildings are responsible for most of the world's energy consumption (ALIM et al., 2019; WANG et al., 2018). Therefore, the concept of the Zero Energy Building (ZEB) (ALMEIDA et al., 2016; BELUSSI et al., 2019; COLLARES-PEREIRA; RABL, 1979; D; KALTENBRUNNER, 2016; FENG et al., 2019; LI et al., 2019; LIU et al., 2020; WELLS; RISMANCHI; AYE, 2018) makes perfect sense because the reduction in the energy demand of buildings in the distribution utility grid reduces the need to build large generating plants to feed urban centers. The application of PV systems to the building envelope is an adequate technological solution to supply electricity to buildings and can occur in two different approaches: building-applied photovoltaic systems (BAPV) and building-integrated photovoltaic systems (BIPV). BAPV is a term used when the installation of PV modules is done on existing roofs, that is, their application is made on a previously designed surface that typically had not been designed for a PV system; therefore, they do not necessarily follow the original characteristics of the architecture or construction. In BIPV systems, photovoltaic modules are inserted in the architecture from the project design stage and aim to integrate as much as possible the solar PV generation with the building architecture, maintaining the aesthetics and function through the use of PV technologies that can replace some constructive materials such as walls and fences, roofs, shading devices or facades. (ADARAMOLA; VÅGNES, 2015; ALIM et al., 2019; AYOMPE et al., 2011; MANOJ; SUDHAKAR; SAMYKANO, 2019; PORTOLAN; RÜTHER, 2012; WANG et al., 2016; WEN et al., 2017; ZOMER et al., 2020, 2013).

The average levels of Global Horizontal Solar Irradiation (GHI) recorded in Brazil are among the best in the world, reaching in excess of 2,230 kWh/m².year (PEREIRA et al., 2017). The lowest annual solar irradiation averages in the Brazilian territory are recorded in the Southern region of the country, as shown in Figure 3.1.

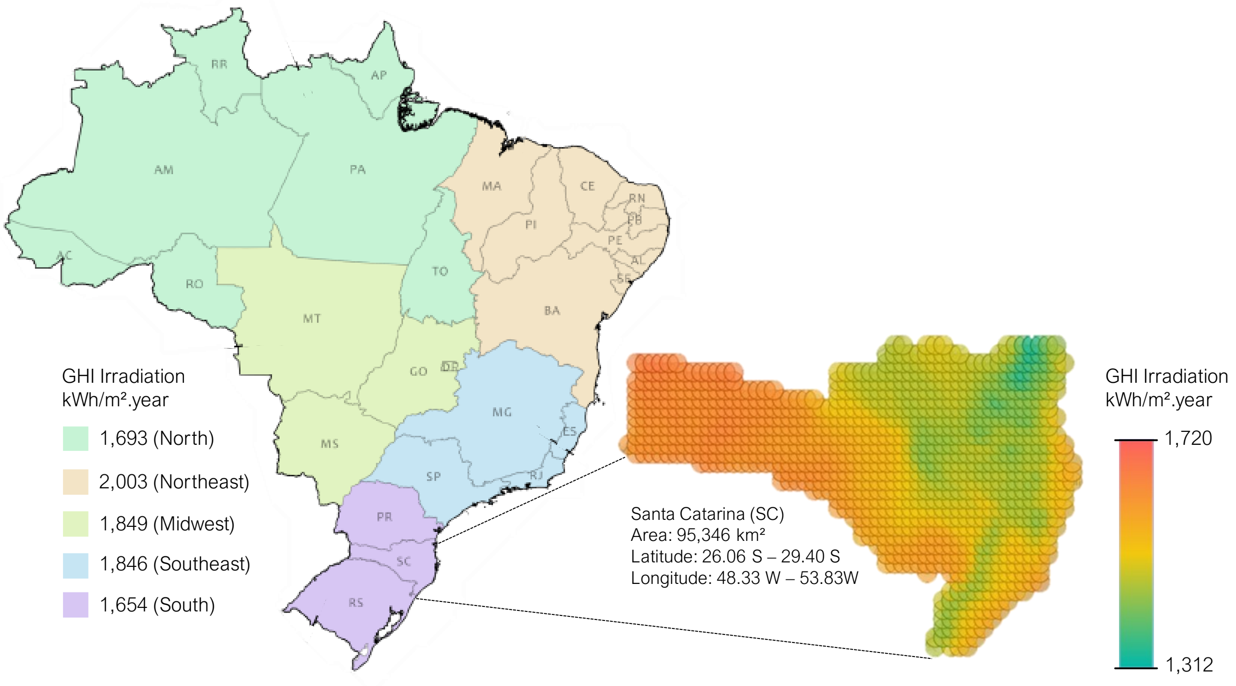


Figure 3.1. Average levels of Global Horizontal Irradiation in Brazil and in the State of Santa Catarina (South Region). Adapted from (PEREIRA et al., 2017).

Although Brazil has great potential for the use of solar energy and PV technologies, there is still much to be done to consolidate solar PV generation in the energy mix, due to the existence of technical, economic, social, managerial, and political barriers. Among the main barriers identified are the high cost of the initial investment, the dependence on financing to buy solar equipment, the consumer culture, somewhat inefficient after-sales services, the dependence on imports of PV modules from Asia, and the lack of more effective policies to encourage PV generation (GARLET et al., 2019). However, due to the reduction in PV technology prices observed in recent years, the adoption of PV generation in buildings in Brazil has increased considerably. In early 2022 Brazil will reach the landmark of over 1 million rooftop PV systems, ten years after legislation made it possible and legal to connect PV generators to the public distribution utility grid (ANEEL, 2022).

The Brazilian distributed generation (DG) Market for small producers started in 2012, with the National Electricity Regulation (ANEEL) Normative Instruction (RN) 482/2012 (ANEEL, 2012), which created and regulated a net metering, Electrical Energy Compensation System (EECS) in the country. Subsequently, in 2015, the publication of RN 687/2015 authorized projects with multiple consumer units, shared generation and remote self-consumption (ANEEL, 2015). This paved the way to new business model developments in shared generation in the country. Stakeholders can join in a consortium or cooperative, aiming to produce their own energy through a so-called microgeneration (up to 75 kW connected at the low-voltage distribution utility level) or minigeneration (between 75 kW and 5 MW at the distribution utility medium-voltage level) PV distributed generator. With the massive price reductions experienced by PV technologies in recent years, rooftop PV generation is increasingly accessible to Brazilian consumers, partly due to DG systems whose economic viability in Brazil has been made possible through EECS, where the active energy injected into the grid by the prosumer is subsequently offset with the consumption of active energy from the same consumer unit or from another unit of the same ownership. This energy credit (in kWh) must be consumed/redeemed within a maximum period of 60 months.

From the consumer's perspective, DG represents savings in electricity costs. With this, a new agent was born in the electricity scenario, the prosumer (producer + consumer), interested in investing in self-generation (GAUTIER et al., 2019; HAHNEL et al., 2020; MATEO et al., 2018; MOURA; BRITO, 2019; OSSENBRINK, 2017). From the perspective of the distribution utility company, DG is often seen as a threat to the business model traditionally practiced. However, more and more electricity distribution companies are considering DG-PV as a new opportunity, rather than a risk to their old model, as utilities develop new business models in order to enjoy the benefits that DG-PV can bring to the distribution system (CARSTENS; CUNHA, 2019; KUZNETSOVA; ANJOS, 2020; ROULOT; RAINERI, 2018). From the consumer's perspective, technical-financial analyses on the adoption of PV systems in different climatic conditions in Brazil and elsewhere in the world are found in the literature (LACCHINI; ANTONIOLLI; RÜTHER, 2017; LACCHINI; RÜTHER, 2015; LÓPEZ PROL; STEININGER, 2020; VALE et al., 2017). Evaluations from the utility's perspective in Brazil are also found in the literature (NASPOLINI; RÜTHER, 2012, 2017, 2019; VAZQUEZ; HALLACK, 2018). However, the literature lacks in-depth analysis and methods to assess the role and benefits of this new agent (prosumer) into the context of distributed generation. This paper aims to evaluate, from the utility's perspective and from the prosumer's perspective, the technical-economic impacts provided by the adoption of solar PV generation in Brazil. To that end, a case study was developed in a residential household of the "CELESC PV Bonus" project, carried out in the State of Santa Catarina – Brazil, into the framework of the Energy Efficiency Program of the local distribution utility (CELESC), in the period from January to December 2019.

This article presents a methodology to assess, both from the distribution utility's and from consumer's perspective, the impacts of solar PV generation adoption in households into the context of the Brazilian electricity market regulation. It is important to emphasize that this paper presents a survey that applies throughout the territory of a continental country with over 8.5 million km². The importance and also the lack of this type of scientific information were diagnosed in a review of the literature, and reinforced by Li *et al.* (2020) in their article entitled *"Sustainability or continuous damage: a study of the behavior of consumers' electricity consumption after the installation of distributed domestic energy resources".* The study reported the impact of households' distributed energy resources on residential electricity consumption and the diminishing effect of electricity generation on the consumption unit.

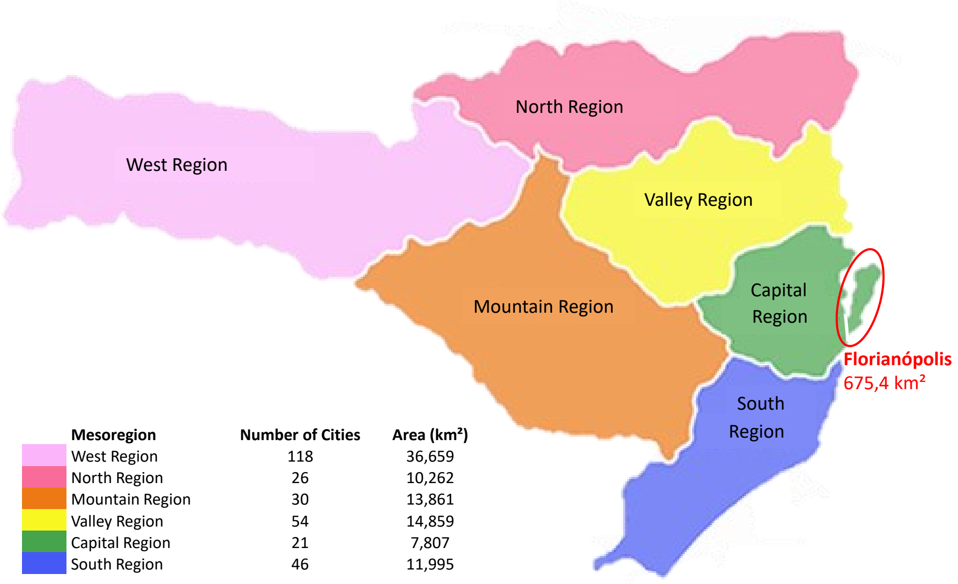
3.2 Case study

3.2.1 CELESC PV bonus project

The CELESC PV Bonus Project (CELESC, 2017) was carried out by the local distribution utility CELESC's Energy Efficiency Program and was operated under bidding and contract by the French-Belgian multinational company *ENGIE Geração Solar Distribuída*. The Project aimed to encourage single-family residential consumers to generate their own energy through solar photovoltaics, increase distributed generation (through the EECS), and promote energy efficiency. Initially the project provided the installation of 1,000 PV household systems. However, due to the great acceptance and consequently to the high number of registrations in the program (over 14 thousand registrations in 48 hours), and also due to the continuing cost reductions experienced by the PV technology in the period, a total of 1,250 identical PV systems of 2.65 kWp each were installed. For each PV kit system installed, the utility provided for the consumer a financial benefit of 60% of the total cost (US$ 4,673). After installation of the PV kits, the project included a minimum period of monitoring under contract; therefore, the consumer was aware that he could not uninstall the system, nor remove the internet connection until the end of 2019.

In order to participate in the project, it was necessary to meet some requirements, such as: (a) the Consumer Unit should be exclusively residential and in compliance with CELESC regulations; (b) the average consumption over the 12 months prior to the registration data should be at least 350 kWh/month; (c) the households in which the identical PV kits would be installed should have a rooftop with enough available area to place 10 x 265 W PV modules (100 x 160 cm or 1,6 m^2), that is, some 20 m^2 continuous free of shading; and (d) the tilt of the rooftop where the modules would be installed should be between 15 and 35 degrees, and oriented towards the Equator with a maximum azimuth deviation of 30 degrees to the East or West.

The distribution of PV households in Santa Catarina was made according to the division of the State into mesoregions and the Prosumer Unit (PU) case study is in the Capital city, on the island of Florianopolis, as shown in Figure 3.2.



	Mesoregion	Number of Cities	Area (km²)
🟪	West Region	118	36,659
🟥	North Region	26	10,262
🟧	Mountain Region	30	13,861
🟨	Valley Region	54	14,859
🟩	Capital Region	21	7,807
🟦	South Region	46	11,995

Figure 3.2. Location of the PU city and mesoregions of the State of Santa Catarina participating in the CELESC PV Bonus Project. Source: (IBGE, 2020).

The Santa Catarina island covers an area of 424.4 km², with an average length of 54 km (North-South) and an average width of 18 km (East-West). The island occupies most of the territory of the city of Florianópolis, which extends across the mainland, and has a total area of 675.4 km².Figure 3.3 shows the map of the city of Florianópolis with the coordinates of 184 identical PV systems that were installed in the region through the CELESC PV Bonus program. The location of the residence case study in this article stands out in red.

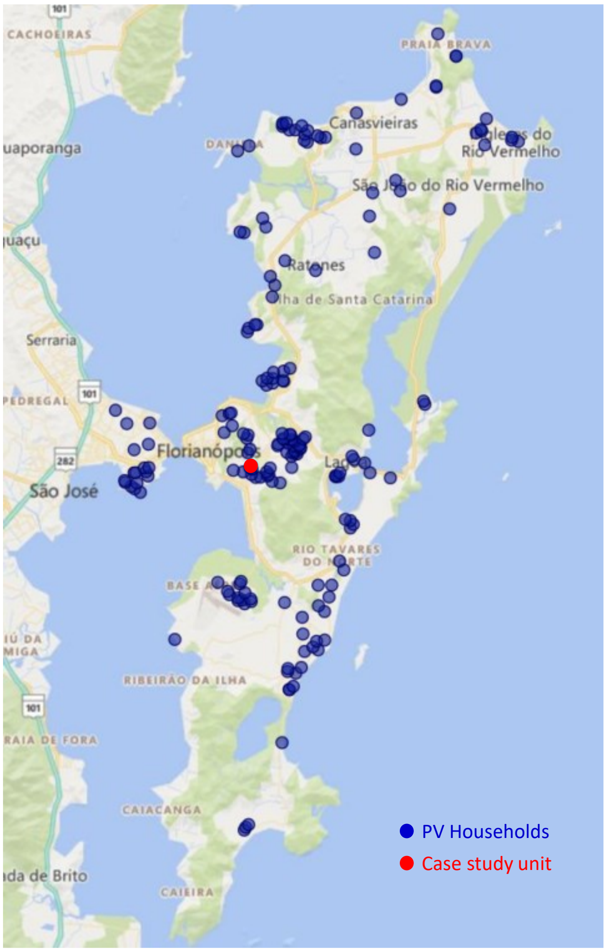


Figure 3.3. Location of 184 PV microgenerators within the city of Florianópolis, as well as the location of the unit that was assessed individually in the case-study presented here.

3.2.2 Description of the PV household in the CELESC PV bonus project

The higher-middle class, single-family, residential household case-study has a configuration of three bedrooms, a built area of 250 m², with an average monthly income above the average income of Brazilian families, estimated in US$ 1,400/month (IBGE, 2019). It is located in Florianopolis – SC – Brazil (27,6° S / 48,5° W), which is classified as Cfa (hot summer) in the Köppen-Geiger climate classification (ALVARES et al., 2013). Its architectural project was conceived considering the use of solar energy, both thermal and photovoltaic. The choice of uphill land oriented to the North was one of the first design guidelines focused on the solar use in this household, minimizing the interference of shading from the surroundings, even with possible changes or new constructions in the neighborhood. The concept of bioclimatic architecture and reduced energy consumption were guidelines in the initial stages of the project.

The building has a Northwest orientation, with: (a) solar water heating collectors on a lower roof below the hot water storage tank, allowing natural convection; (b) PV modules on the upper rooftop. Figure 3.4 shows different angles for the 2.65 kW building-applied photovoltaic system (BAPV).

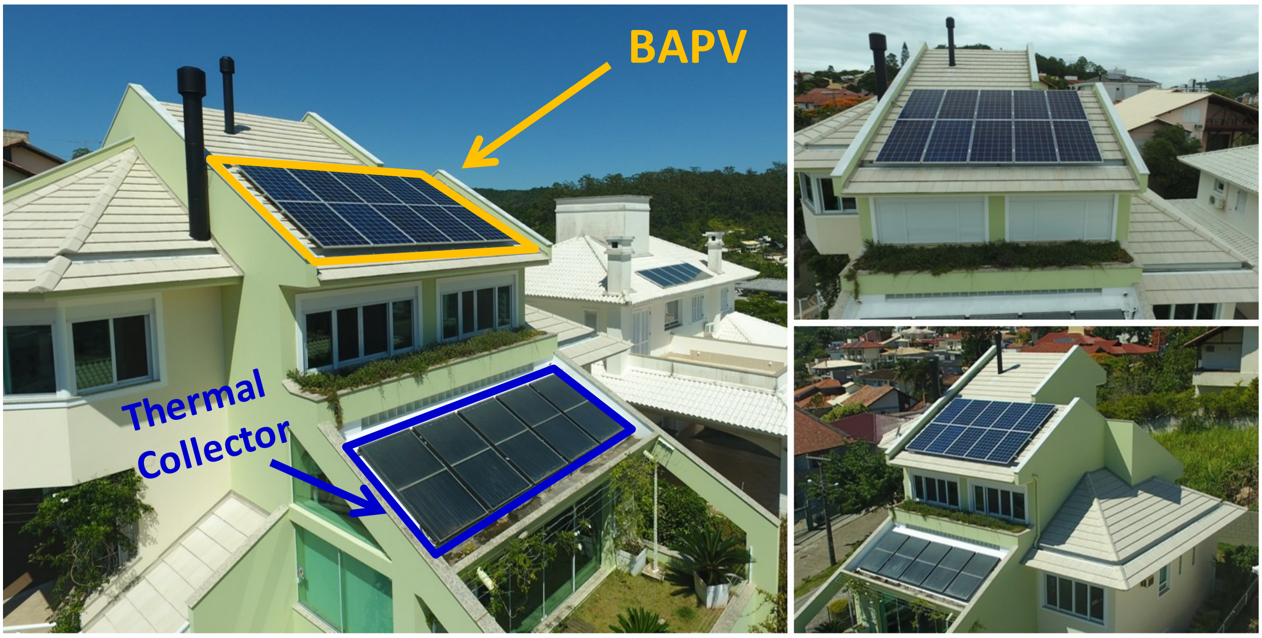


Figure 3.4. Solar PV (upper roof) and solar water heating collectors (lower roof) applied to the case-study household roof.

In the design stage, it was defined that the PV system would be applied over the rooftop painted white (30 degrees East of azimuth deviation), with a 28 degrees tilt (approximate latitude of Florianópolis). For the installation of the thermal solar collector system, with a 500 liters capacity, an area of approximately 10 m² was allocated.

The roofing materials for houses in southern Brazil are typically ceramic or fiber-cement tiles. In this case-study, the fixing of PV modules to the roof was done through a metallic structure ensuring a 10 cm spacing between modules and ceramic tiles. This way, there is ventilation under them, and the heat can be dissipated more easily, and losses minimized. It is worth mentioning that the PV system is free of shading, since not even the nearby chimneys cause shadows on the modules, at any time of the year.

The PV kit applied to the upper roof is composed of 10 PV modules and one inverter with a ±4% accuracy in output electrical values. Tables 3.1 and 3.2 show the characteristics of the PV modules and Table 3.3 shows the characteristics of the inverter. Energy measurements were made at the prosumer unit point of connection with the local distribution utility (CELESC), through a bidirectional electronic polyphase meter (E34A model - Landis+Gyr), of direct measurement, typically used in energy consumers of up to 120A. The device uses Direct Field Senser (DFS) measurement technology with a 1% accuracy class for active energy measurement and is widely used by Brazilian utilities for charging and offsetting credits arising from excess PV generation.

3.3 Methodology

The methodology was divided into five principal stages:

In the first stage, the analysis of the solar resource available in satellite databases (Brazilian Atlas of Solar Energy 2nd edition (PEREIRA et al., 2017)) and of the meteorological station closest to the location of the PV system were carried out. In the second stage, the actual energy generation measured from the PV system was compared with the estimated energy generation (theoretical and via PVsyst® simulations), and the estimated and measured productivity metrics (annual energy Yield and Performance Ratio - PR) were compared. The third stage consisted in analyzing the PU’s monthly electricity bills in the period of one year before the CELESC PV Bonus project, and one year after its end, in order to assess, from the perspective of the distribution utility and the PU, the energetic and financial impacts provided by the adoption of PV. The fourth stage consisted in the evaluation of avoided emissions, expressed in kgCO_2, provided by the adoption of PV. The fifth stage aimed to perform a comparative analysis between the individual PV rooftop case study with the average of PV households in the Florianópolis region.

Both the energy and the financial impacts as well as the environmental impacts provided by the CELESC PV Bonus Project come only from the use of solar PV generation in the household, since there were no other changes implemented. Figure 3.5 shows the flowchart of this paper methodology.

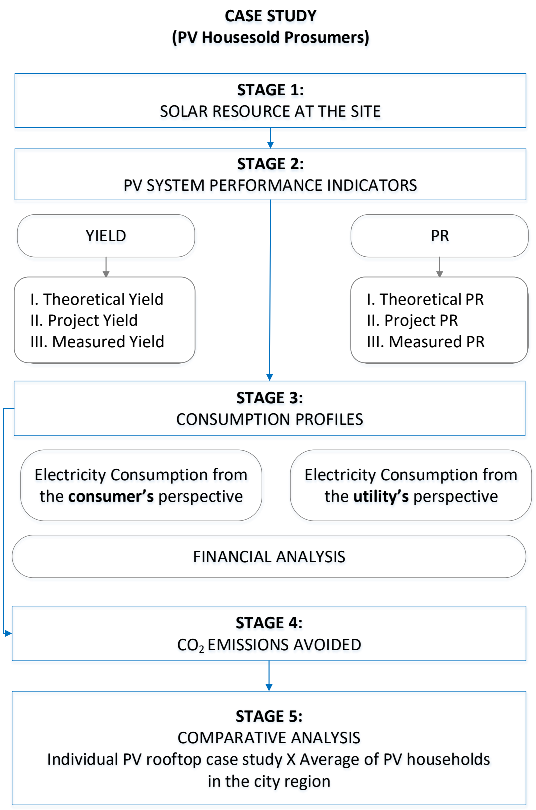


Figure 3.5. Flowchart of the methodology proposed and applied in this paper.

3.3.1 Solar resource at the PU

Knowledge of the distribution of the solar resource throughout the year, for each location and region, is essential for both the development and the dissemination of solar PV technology. Investigations that show the importance of a good analysis of the solar resource in face of the different databases used for sizing PV projects in Brazil were previously published elsewhere (ANTONIOLLI et al., 2014; MOSCARDINI JR; RÜTHER, 2020). For the analyzed period and for the Florianopolis site, the methodology adopted consisted in using data from two sources: (i) Brazilian Solar Energy Atlas, 2nd edition (PEREIRA et al., 2017), which presents satellite data provided by the Brazilian National Institute of Space Research (in Portuguese, *Instituto Nacional de Pesquisas Espaciais* – INPE), with spatial resolution of 0.1 x 0.1 degrees (approximately 10 x 10 km), presented through the Geographic Coordinate System SIRGAS1 2000 and; (ii) Universidade Federal de Santa Catarina – UFSC´s meteorological station (COLLE, 2007), with measured irradiance data at one-minute resolution using CM11 Kipp & Zonen pyranometers. The analyzed period comprises the historical series of ten years of ground measurements (2009 to 2019) and the ground measurements from January to December 2019.

On days when the UFSC station records missed data, the gap filling methodology of Schwandt (SCHWANDT et al., 2014b) was used. The data filling procedure for missing data of up to 10 days consisted in replacing the failures of the first five days with data from the day before the failure started, and the last five days of failure with data from the day after the failure. The limit of 10 days is defined since it is assumed that the weather might remain constant for a period of up to five days. In addition, the relative position of the sun does not deviate significantly over a period of five days.

GHI, at one-minute intervals, was calculated according to Equation 3.1.

$$Irr = I \times \frac{1}{60} \qquad \text{(Eq. 3.1)}$$

where:

Irr = GHI solar irradiation, in one-minute intervals, in Wh/m²;

I = Horizontal plane irradiance, in one-minute intervals, in W/m².

The calculated GHI, in the specified time interval, can be obtained through Equation 3.2.

$$Irr_{Total} = \sum_{k=1}^{i} Irr_k \qquad \text{(Eq. 3.2)}$$

where:

Irr_{Total} = GHI solar irradiation in the specified interval i,in Wh/m²;

Irr_k = GHI solar irradiation, in the time interval k integral of the specified time interval, in Wh/m²;

i = Upper limit of the sum;

k = Lower limit of the sum. Generic index representing the period k=1 to i.

The GHI is characterized as the sum of the global horizontal solar irradiation values calculated at each one-minute interval, part of the specified time interval (k, i). The UFSC meteorological station is located at 0.87 km from the PV system, as shown in Figure 3.6.

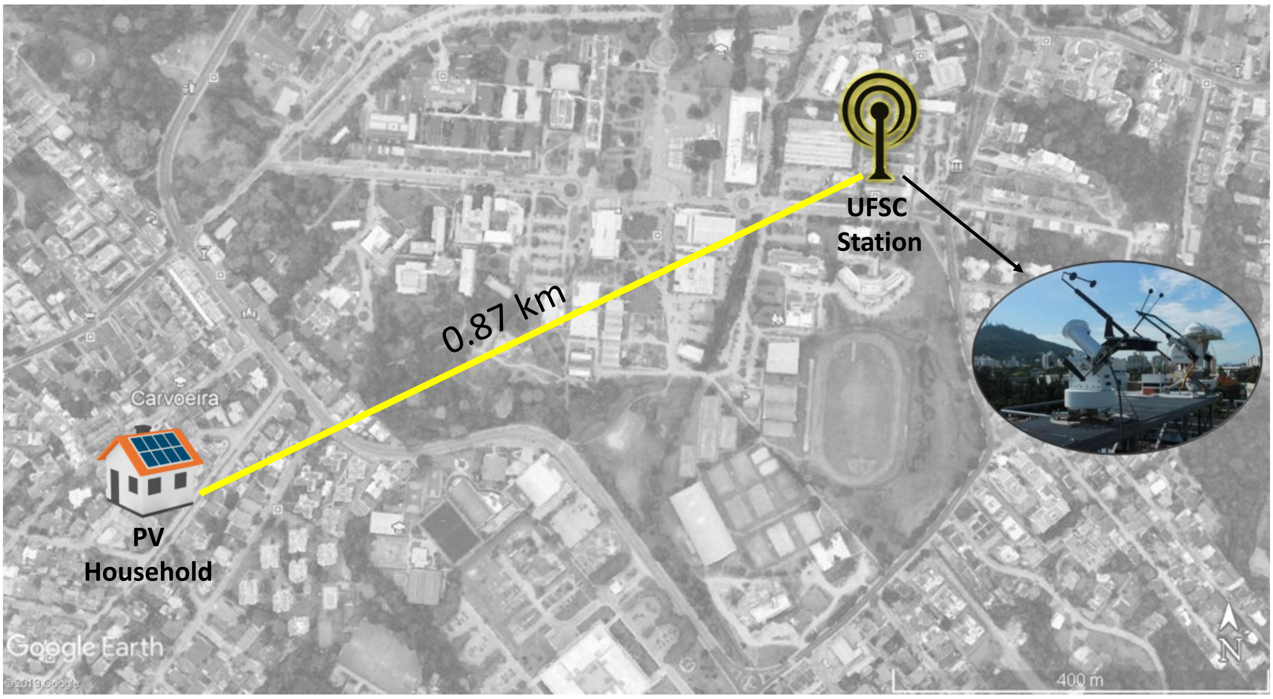


Figure 3.6. Distance between the case-study PV residence and the UFSC meteorological station.

After the stage of data acquisition and data processing, the analysis of the inter-annual variability of GHI was carried out using the measured data from the UFSC meteorological station. For that, data were integrated at one-minute intervals, on a monthly basis (kWh/m².month), and differences were compared, month by month, between January and December of the historical average (2009 to 2019) and from January to December of the year 2019, as well as the total annual difference, aiming to show the inter-annual and inter-seasonal variability of solar irradiation at the site.

Then, the measured data were transposed, using the Perez mathematical model (PEREZ et al., 1987) using the Radiasol software tool (KRENZINGER, 1998) for two situations: (i) Ideal theoretical conditions for the installation of a PV system, that is, tilt equal to the local latitude and zero azimuth deviation; (ii) Real conditions of GHI to plane-of-array (GPOA) of the PV modules, with 28 degrees tilt and azimuth 30 degrees due East. In the case of the ideal theoretical condition, the Global Tilt Irradiation (GTI) values extracted from the satellite database (Brazilian Solar Energy Atlas (PEREIRA et al., 2017)) were used in the simulations. The GTI is equivalent to local latitude, that is 27.59 degrees, and these data are available for free and public download.

3.3.2 PV system performance indicators

This section aims at evaluating the Productivity (Annual Energy Yield, in kWh/kWp.year) and Performance Ratio (PR, in %)) of the residential household PV rooftop system generation.

3.3.2.1 Productivity (Annual Energy Yield)

The yield assessment was divided into three stages:

I – Theoretical Productivity Estimate (Theoretical Yield): Through Equation 3.3, it is possible to estimate a theoretical yield, which represents the amount of energy that would be generated for each installed power unit (kWh/kWp). In the estimates of theoretical yield, GTI data from the satellite database (Brazilian Solar Energy Atlas) and from ground measurement database (UFSC station) were used. In this case, a typical theoretical value of 80% was adopted for theoretical annual PR (Performance Ratio) (MARION et al., 2005; REICH et al., 2012).

$$\mathrm{Yi} = \mathrm{PR} \cdot \frac{\mathrm{GTI_i}}{\mathrm{Irr}_{STC}} \qquad \text{(Eq. 3.3)}$$

where:

Y_i = Yield of the PV generation, in the specified time interval i, in kWh/kWp;

PR = Performance Ratio (0.8)

GTI_i = Tilt irradiation, in the specified time interval i,in kWh/m²

Irr_{STC} = Irradiance under Standard Test Conditions - STC = 1 kW/m².

II – Project Productivity Estimate (Project Yield): The project yield was simulated, using the PVsyst® software, for two irradiation scenarios: (i) irradiation data from the Brazilian Solar Energy Atlas; (ii) on site measured irradiation data from Jan to Dec/2019. In the simulations, the electrical configurations of the CELESC PV Bonus kit and the standardized system losses were used as input data for the project.

Table 3.1 and Table 3.2 present, respectively, the characteristics of the PV modules and the standardized losses (including current and temperature losses) adopted in the simulations by PVsyst® for the PV household system analyzed. Table 3.3 shows the inverter characteristics.

Table 3.1. PV modules characteristics (JAP6-60-265/4BB).

Technology	Power (W)	Vmpp (V)	Impp (A)	Voc (V)	Isc (A)
Multicrystalline Silicon (p-Si)	265	138	17	38.05	9.08

Table 3.2. Standardized losses adopted for the PV system connected to the power grid.

Technology	Ohmic Loss	Mismatch losses	Soiling losses	System Unavailability	LID losses	Short circuit current (%/°C)	Open circuit voltage (%/°C)	Max. temperature coefficient (%/°C)
Multicrystalline Silicon (p-Si)	0.015	0.001	0.03	0.007	0.03	0.00058	-0.0033	-0.41

Table 3.3. Inverter characteristics (UNO-3.0-TL-OUTD).

Inverter Power	Absolute max. DC input voltage ($V_{max,abs}$)	Start-up DC voltage (V_{start})	Max. DC input current	MPPT input DC voltage range	Number of independent MPPT
3 kW	600	100...300 V (default 150 V)	16.0 A	200...500 V	1

III – Measured Productivity (Measured Yield): The calculation of the measured yield of the PV system can be performed using Equation 3.4 and measured output performance data. The period analyzed comprised the months from Jan to Dec/2019.

$$\mathrm{Yi} = \frac{\mathrm{E_{PVi}}}{\mathrm{P_{PV}}} \qquad \text{(Eq. 3.4)}$$

where:

Y_i = Yield of the PV, in the specified time interval i, in kWh/kWp;

E_{PVi} = PV solar energy generated, in the specified time interval i,in kWh;

P_{PV} = Installed PV power (= 2.65 kWp),in kWp.

The energy production information was extracted via internet communication through the electronic device available on the inverter. The study deals with the evaluation of a large sample of decentralized systems whose only access to information is remote, making use of the PV inverter measurement and internet communication interface.

3.3.2.2 Performance Ratio (PR)

The evaluation of PR was divided into three stages:

I – Theoretical Performance Ratio (Theoretical PR): This paper adopted for theoretical PR the typical value of 80% (MARION et al., 2005; REICH et al., 2012; RÜTHER; VIANA; SALAMONI, 2010).

II – Estimate of the project Performance Ratio (Project PR): The project PR's were simulated, using the PVsyst® software, for two irradiation scenarios: (i) Historical average of satellite Global tilted irradiation data from the Brazilian Solar Energy Atlas which presents an average of 17 years of 900 meteorological data collection stations added to another 17 high definition stations (five of which are in the state of Santa Catarina) controlled by the National Institute for Space Research - INPE), and; (ii) The monthly average of irradiation data measured at the site (presented by Figure 3.6) from Jan to Dec/2019.

III – Measured Performance Ratio (Measured PR): The calculation of the measured PR was performed through Equation 3.5. The period analyzed comprises the months from Jan to Dec/2019.

$$\mathrm{PR}_i = \frac{\mathrm{E_{PVi}}/\left(\frac{\mathrm{G_{POAi}}}{\mathrm{Irr_{STC}}}\right)}{\mathrm{P_{PV}}} \qquad \text{(Eq. 3.5)}$$

where:

PR_i = Performance Ratio of BAPV, in the specified time interval i;

E_{PVi} = PV solar energy generated, in the specified time interval i, in kWh;

G_{POAi} = GHI to plane-of-array of the BAPV modules, in the specified time interval i, in kWh/m²;

Irr_{STC} = Irradiance under Standard Test Conditions-STC = 1 kW/m²;

P_{PV} = Installed PV power (= 2.65 kWp), in kWp.

3.3.3 Consumption profiles of the PU

The prosumer is a new agent that has been emerging into the regulated market for distributed electricity generation. In this case, the old consumer unit also becomes a generating unit and the distribution utilities begin to see PU's in a different way. In this paper, profiles of consumption and of the surplus PV energy fed into the public grid by the PU, are analyzed from two perspectives: (i) Utility's perspective: which monitors the behavior of the household only by the electricity meter, located on the frontier between the grid and the PU, and; (ii) Prosumer's perspective: which has PV generation with simultaneous reduction in consumption, surplus electricity injected into the utility's grid and consumption from the electricity grid.

3.3.3.1 Electricity consumption and expenses profiles of the PU from the Utility's perspective

From the Utility's perspective, using the PU's electricity bills, profiles of electricity consumption and surplus PV energy fed into the grid were raised in the period from Jan to Dec/2019 (one year after the installation of the PV system on the household rooftop), and consumption profiles in the period from Jan to Dec/2017 (one year before the PV system was installed), because the monthly consumption for the year 2018 does not represent the consumption before installation, since they were installed throughout that year. In addition, the impacts provided by the addition of the PV generation to the PU electricity expenses were evaluated.

3.3.3.2 Electricity consumption and expenses profiles of the PU from the Consumer's perspective

From the Consumer's perspective, using the PU's electricity bills, profiles of electricity consumption and surplus PV energy fed into the utility's grid were raised. The PV generation profiles, both for the period included between Jan and Dec/2019 (one year after PV generation was installed at the household) and consumption profiles in the period between Jan and Dec/2017 (one year before PV generation was installed at the household). In addition, the impacts from the addition of the PV generation to the PU electricity expenses were evaluated. In this case, the PU, powered by a three-phase low voltage grid, is required to pay a minimum cost of grid availability equivalent to the consumption of 100 kWh, according Normative Instruction RN 414/2010 (ANEEL, 2010). The active energy injected into the network is subsequently offset with the consumption of active energy from the same consumer unit or from another unit of the same ownership. This credit in the quantity of active energy (kWh) must be consumed within a maximum period of 60 months.

If the PU consumption is greater than the generation at the instant analyzed, Equation 3.6 is used. In the opposite situation, Equation 3.7 is used. For the PU consumption after the PV integration, during the analyzed period, Equation 3.8 was used.

$$\text{Grid Consumption}_{\text{total}} = \sum_{i=1}^{k} \text{Grid Consumption}_{i} \qquad \text{(Eq. 3.6)}$$

$$\text{PV Generation Consumption}_{\text{total}} = \sum_{i=1}^{k} (\text{GenPV}_{i} - \text{Ener}_{\text{Inj}_{i}}) \qquad \text{(Eq. 3.7)}$$

$$\text{Consumption}_{\text{total}} = \text{Grid Consumption}_{\text{total}} + \text{Generation Consumption}_{\text{total}} \qquad \text{(Eq. 3.8)}$$

where:

Consumption_i = Consumption of PU in the specified time interval i, in kWh.

$\text{Grid Consumption}_i$ = Electrical energy consumption from the public utility CELESC (bill), in the specified time interval i,in kWh.

GenPV_i = PV energy generated from the UP, in the specified time interval i,in kWh.

Ener_Inj_i = Surplus energy fed into the public utility CELESC's electricity network (bill), in kWh.

$\text{Consumption}_{\text{total}}$ = Consumption total of PU in the specified time interval k, in kWh.

PV Generation Consumption$_{total}$ = Electrical energy consumption of PV energy generated in the specified time interval k, in kWh.

For photovoltaic generation, initially the energy values (kWh) were integrated in five min. intervals, and then integrated in the specified time interval (hourly-daily-monthly). For consumption, the amounts were taken from electricity bills issued by the local distribution utility (monthly).

3.3.4 Financial analysis of Return on Investment (ROI)

The financial analyses of the Return on Investment made for the addition of the PV system in the household were made through simulations of the payback time on the investment, the Net Present Value (NPV), and the Internal Rate of Return (IRR). These were calculated for different rates of return on capital, as shown in Equations 3.9, 3.10 and 3.11. The levelized cost of energy (LCOE) can be calculated through Equation 3.12.

$$\mathrm{CPV(t)} = -\mathrm{I} + \sum_{j=1}^{t} \frac{(\mathrm{Rj}-\mathrm{Cj})}{(1+i)^{j}} \tag{Eq. 3.9}$$

$$\mathrm{NPV} = \mathrm{CPV(n)} \tag{Eq. 3.10}$$

$$\mathrm{NPV} = 0 = \mathrm{I} + \sum_{j=1}^{t} \frac{\mathrm{CPV}}{(1+\mathrm{IRR})^{j}} \tag{Eq. 3.11}$$

$$\mathrm{LCOE} = \frac{\left[\sum_{j=1}^{n} \frac{C_j}{(1+i)^{j}}\right]+\mathrm{I}}{\sum_{j=1}^{n} \frac{E_j}{(1+i)^{j}}} \tag{Eq. 3.12}$$

where:

$1 \leq t \leq n$

CPV (t) = Capital present value, in US$;

NPV = Net present value, in US$;

I = Initial investment, in US$;

R_j = Revenue of year j, in US$;

C_j = Cost of year j, in US$;

E_j = Generated energy, in the year j, in kWh;

▯ = Annual interest rate;

j = Generic index representing the period j = 1 to t;

n = Equipment lifespan, in years;

IRR = Internal rate of return.

3.3.5 Adoption of PV generation in the PU to promote the energy efficiency

The CELESC PV Bonus project was carried out under the scope of CELESC's Energy Efficiency Program. The project aimed to encourage single-family residential consumers to generate their own energy through photovoltaics, increase distributed generation (through the injection of surplus PV energy into the Utility's grid) and promote energy efficiency.

For the Utility, the annual Energy Savings (ES) and the annual Demand Reduction during Peak hours (DRP) provided by the project are the main technical indicators to evaluate the project from the perspective of energy efficiency (ANEEL, 2008, 2013).

This paper adopts the same definition for the peak hours of the local electric utility CELESC, that is, for the weekdays, the period between 18:30 and 21:29 (CELESC, 2019). Despite not meeting peak hours, the project is part of the energy efficiency program due to the energy savings from photovoltaic generation integrated into the building.

From the Utility's perspective, the contribution of solar PV generation in the household does not reduce the demand during peak hours, due to the low solar irradiation verified at the end of the day. The energy saved coincides with the energy generated by the PV generator.

3.3.6 CO_2 emissions avoided

The avoided emissions of greenhouse effect gases, expressed in tons of equivalent CO_2, are the main technical indicators to assess the environmental impacts provided by the surplus electricity into the grid (NASPOLINI; RÜTHER, 2012; UUSITALO et al., 2017). This paper analyzed the adoption of solar PV generation by the residential consumer. Avoided CO_2 emissions, in the period i, were calculated according the Brazilian electrical sector (MCTIC, 2019), using Equation 3.13, for the period between Jan and Dec/2019.

$$\mathrm{CO}_{2\mathrm{i}} = \mathrm{EPV}_{\mathrm{i}} \times \mathrm{F}_{\mathrm{i}} \qquad \text{(Eq. 3.13)}$$

where:

CO_{2i} = Avoided greenhouse gas emissions in period i, in $tCO_{2equivalents}$;

EPVi = PV energy generated in period i, in MWh;

F_i = Average emission factor of the SIN, in period i, in tCO_2/MWh.

Table 3.4 presents, for the Brazilian electrical system generation mix, and for the period between Jan and Dec/2019, the inventory of the average equivalent CO_2 emission factors, expressed in tons of CO_2/MWh, calculated, and made available by the National Interconnected System (SIN). Its calculation considers the fossil fuel-based participation in Brazilian electricity production at the SIN.

Table 3.4. Average emission factors of CO_2 (tCO_2/MWh) – Base year 2019. Source: (MCTIC, 2019).

Monthly											
JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0.0355	0.0667	0.053	0.0514	0.0482	0.0426	0.0906	0.107	0.1024	0.104	0.1078	0.0913

3.3.7 Comparative analysis between the individual PV rooftop case study and average of PV households in the Florianópolis region

In this step, a methodology was used to analyze the energy generation data of the sample of 184 identical PV systems located in the same city that is the object of study of this article. Through technical and statistical filters, it was possible to validate a significant sample of systems. The technical filters used hourly generation values as input data and were divided into three steps: (i) Daily data validation: counts the number of hourly records over eight hours with a minimum of 50 W and validates an acceptable day of recordings for each PV generator; (ii) Monthly data validation: counts the months of systems with at least 15 days of valid daily data; (iii) Annual data validation: accounts for PV systems with 12 months of valid monthly data. The statistical filter aims to eliminate outliers and thereby obtain a more adjusted normal distribution. After confirming the normal distribution, the following equations apply:

$$M_a = \frac{\sum_{i=1}^{N} x_i}{N} \qquad \text{(Eq. 3.14)}$$

$$S = \sqrt{\frac{\sum_{i=1}^{N} (x_i - M_a)^2}{N}} \qquad \text{(Eq. 3.15)}$$

$$\text{Erro} = Z_{\frac{\propto}{2}} \frac{S}{\sqrt{N}} \qquad \text{(Eq. 3.16)}$$

Where:

1<i<n

N = Number of sample elements

x_i = Data value

M_a = Arithmetic average

S = Sample standard deviation

Erro = Sample error interval

α = Significance level (0.05), typically used for analyzes like this (HEESEN; HERBORT, 2016)

$Z_{\alpha/2}$ = Table Z value associated with α (Z0, 025 = 1.96)

The monthly and annual averages of the sample of the PV systems validated by the filters were compared with the individual performance of the PV roof of the residence studied in this article.

3.4 Results

3.4.1 Solar resource at the PU site

Figure 3.7 shows the average measured values of the GHI in the period between 2009 and 2019 and GHI measured in the year 2019, from data recorded by the Universidade Federal de Santa Catarina – UFSC´s solar irradiance measurement station in Florianópolis.

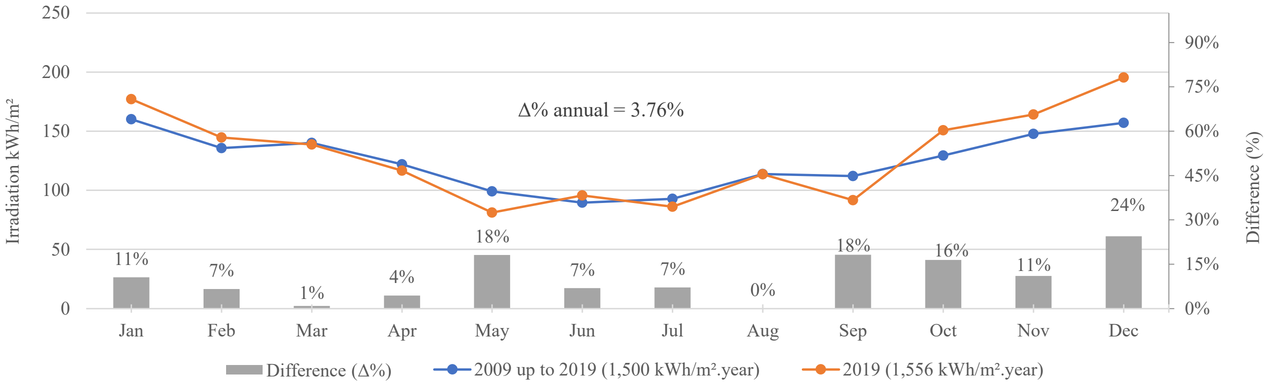


Figure 3.7. Average GHI measured from 2009 to 2019 and GHI measured in 2019 in Florianópolis, Brazil. Database: UFSC Station (COLLE, 2007).

GHI (2009-2019) presented a ten years average value of 1,500 kWh/m².year, and in 2019 GHI was measured at 1,566 kWh/m².year. This less than 5% difference is well within the interannual variability at the site (PEREIRA et al., 2017). The greatest variation between the measured values was verified in December (24%), followed by May and September, both with 18%.

Figure 3.8 shows, for ideal tilt and orientation (tilt equal to latitude and azimuth equal to zero), the mean values of plane-of-array solar irradiation obtained from historical data measured from GHI at the Universidade Federal de Santa Catarina – UFSC´s solar irradiance measurement station (2009 to 2019) and from satellite data. In addition, average values of the real conditions of GHI to plane-of-array (GPOA) of the

PV modules (tilt = 27 degrees and azimuth = 30 degrees due East) are shown. The tilt irradiation and GPOA were obtained through the Perez mathematical transposition, using the Radiasol software (KRENZINGER, 1998).

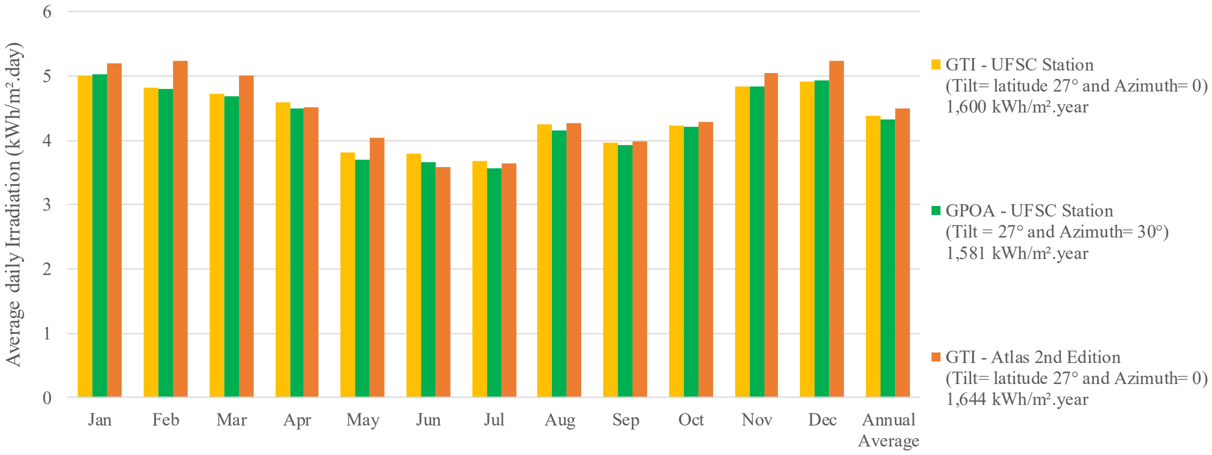


Figure 3.8. Monthly average of the total daily solar irradiation for the ideal orientation GTI condition (UFSC Station and Atlas 2nd Edition) and the irradiation in the plane of the PV modules in Florianópolis, Brazil.

For historical GHI measured by the Universidade Federal de Santa Catarina – UFSC´s solar irradiance measurement station in Florianópolis (1,499 kWh/m².year), the results show for the ideal GTI (1,600 kWh/m².year) and for the plane of the PV modules GPOA (1,581 kWh/m².year). It is noted that the irradiation in the latitude-tilted plane in the GPOA is 6% greater than GHI. The results show, for ideal orientation, a difference of less than 2.7% between the tilted irradiation calculated from data measured at the UFSC weather station and the tilted irradiation obtained from the Brazilian Solar Energy Atlas (1,644 kWh/m².year). It is also observed that the correlation between the irradiation data measured by the UFSC weather station and the satellite tilted data was 0.97, much higher than the correlations typically found in the literature (KARIUKI; SATO, 2018; TIBA; FRAIDENRAICH, 2004).

From the data measured at the ground station, it was observed that irradiation values incident on the PU (1,581 kWh/m².year) did not present a significant difference (1.3%) when compared with the ideal conditions for the PV installation (1,600 kWh/m².year). Therefore, the integration conditions adopted by the CELESC PV Bonus Project for the PV roofs eligible to participate (tilt = 15° to 35° and azimuth = max 30° deviation) are in accordance with the best use of the available solar resource.

3.4.2 Photovoltaic generation at the PU

The photovoltaic generation information is directly reflected on the productivity indicators (Annual Energy Yield) proposed in this article, therefore Figure 3.9 shows the expected and measured generation values at the PV generator case-study: (i) Project generation calculated by the PVsyst® software, which uses historical irradiation data (2009 to 2019) from the UFSC station as input for simulation; (ii) Project generation calculated by the PVSyst® software, using satellite irradiation data (Brazilian Solar Energy Atlas) as input for simulation and; (iii) Measured real PV generation at the PU (Jan to Dec/2019).

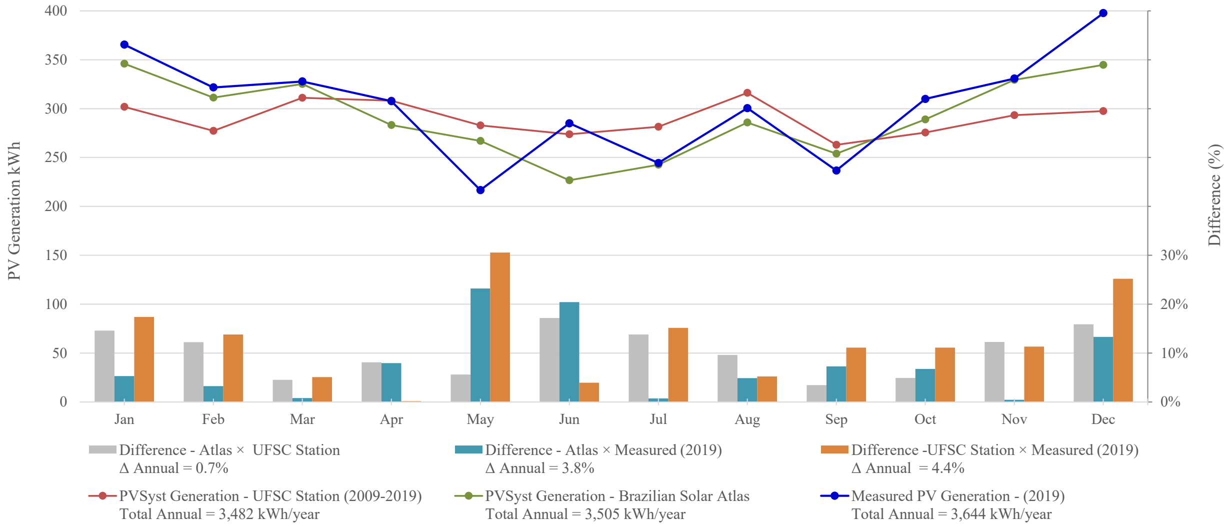


Figure 3.9. Case-study simulated PV generation (irradiation data from Brazilian Solar Energy Atlas and UFSC station) and real measured PV generation in Florianópolis, Brazil.

The results show that the measured PV generation has a difference of less than 5% when compared to the two simulated values using PVSyst®: (i) Δ annual of 3.8% using the Brazilian Solar Energy Atlas database and; (ii) Δ annual of 4.4% using the 10 years UFSC weather station database.

The difference between the two simulated values was 0.7%. Therefore, the PV electricity generation values are in accordance with estimates based on satellite irradiation databases (Brazilian Solar Energy Atlas) and 10 years on ground measurement (UFSC weather station) data.

3.4.3 Annual Energy Yield at the PU

Figure 3.10 shows the monthly evolution of energy yield for four situations: (i) Project Yield (PVSyst®): which uses historical irradiation data from 2009 to 2019 from the UFSC solar irradiance station and satellite irradiation data from the Brazilian Solar Energy Atlas; (ii) Estimated PV Energy Yield (PR = 80%): which uses solar irradiation data from 2009 to 2019 from the UFSC weather station transposed to the plane of the array, adopting a typical PR of 80%; (iii) Theoretical Atlas Yield (PR = 80%): which uses satellite GTI data from Brazilian Solar Energy Atlas, adopting a typical PR of 80%, and; (iv) Measured PV Yield (2019): with the measured yield for real output data, from Jan to Dec 2019, extracted directly from the inverter monitoring platform.

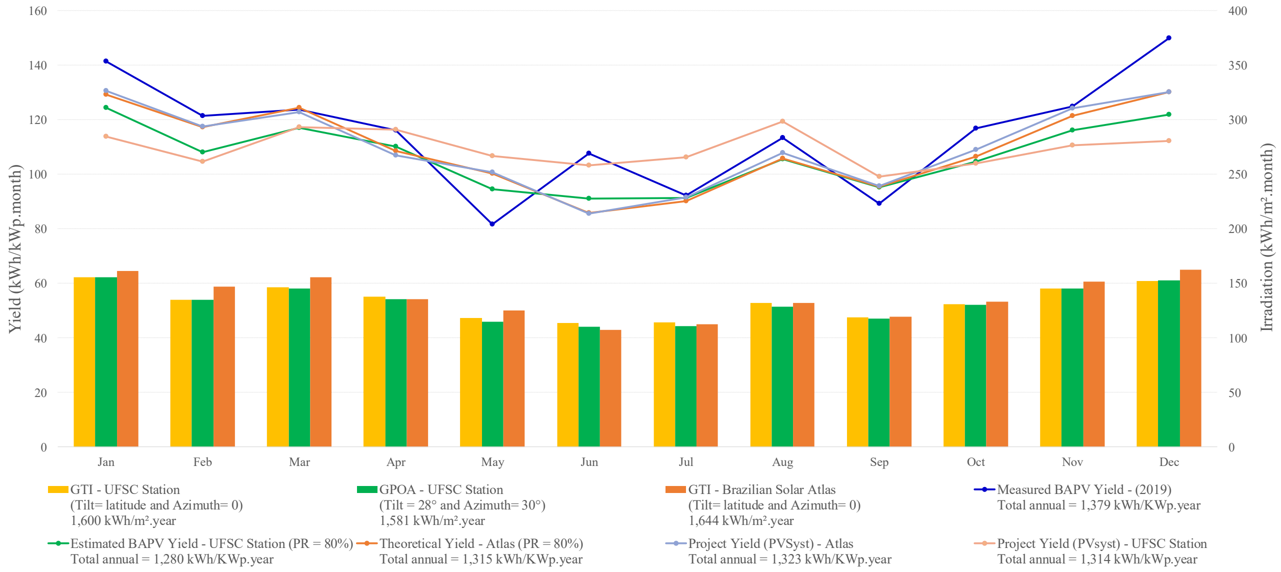


Figure 3.10. Monthly Energy Yield for different situations: Project yield, theoretical yield (UFSC weather station and Brazilian Solar Energy Atlas database), and measured yield (2019).

The results show that for the different situations analyzed, the annual energy yield values were respectively 1,323 kWh/kWp.year for “Project Yield (PVSyst) – Brazilian Solar Energy Atlas”; 1,314 kWh/kWp.year for “Project Yield (PVSyst®) – UFSC Weather Station”; 1,280 kWh/kWp.year for “ Estimated PV Yield – UFSC Weather Station”; 1,315 kWh/kWp.year for “Theoretical Yield – Brazilian Solar Energy Atlas”; and 1,379 kWh/kWp.year for “Measured PV Yield”. It is observed that the annual measured PV yield was 4.8% higher than the theoretical yield expected based on the satellite values.

The energy yield profiles for the situations “Measured PV Yield” and “Estimated PV Yield – UFSC Weather Station” are very similar. However, the values measured on an annual basis were higher than the theoretical expectation (1,379 kWh/kWp against 1,280 kWh/kWp, with a difference of 7.7%). For the situations “Estimated PV Yield – UFSC Weather Station” and “Theoretical Yield – Brazilian Solar Energy Atlas” the results were respectively 1,280 kWh/kWp and 1,315 kWh/kWp, with a difference of 2.7%. Differences in solar radiation databases can be substantial (MOSCARDINI JR; RÜTHER, 2020) and the differences reported here are well within the typical interannual variabilities of sites in the Brazilian territory (PEREIRA et al., 2017). In PVsyst® simulations, they already take temperature losses into account Figure 3.14 presents the maximum and minimum temperatures for each month of 2019.

3.4.4 Performance Ratio (PR)

Figure 3.11 shows the monthly evolution of the project PR for historical irradiation data from 2009 to 2019 from the UFSC weather station and for satellite irradiation data from Brazilian Solar Energy Atlas, as well as for PR calculated with irradiation data measured at the site for the year 2019 (UFSC weather station). These PR values are shown against an 80% typical of the currently best-of-kind PV installations worldwide (REICH et al., 2012).

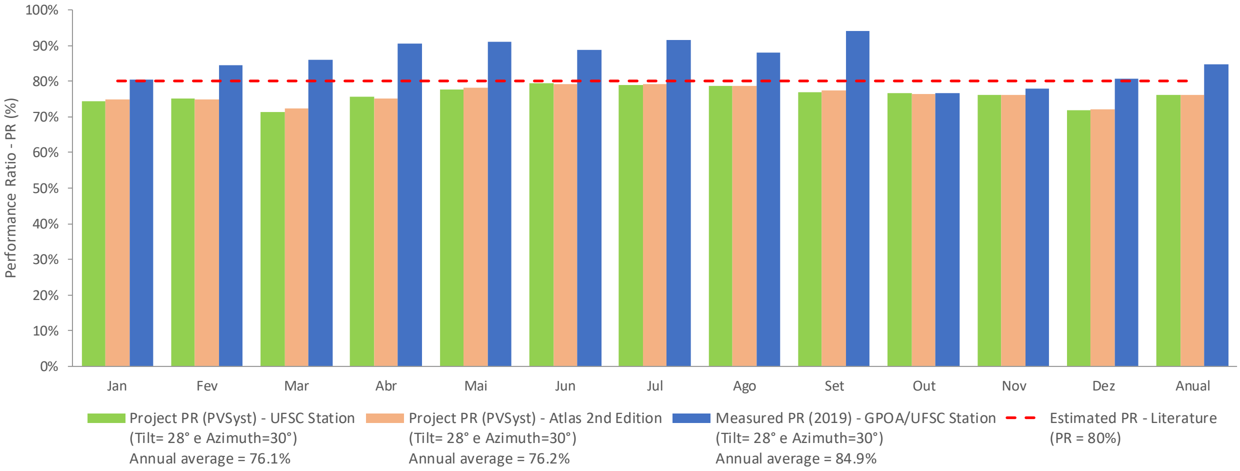


Figure 3.11. Monthly evolution of project PR, measured PR (2019) and best-of-kind PR = 80% (REICH et al., 2012).

It is observed that the average annual project PR, calculated from the simulations made using PVsyst®, presented a value below 80% (theoretical value adopted from literature (REICH et al., 2012)). The average annual values of the project PR, obtained from the historical series of the UFSC weather station and data from the Brazilian Solar Energy Atlas were quite similar, with respective annual PR averages of 76.1% (UFSC weather station) and 76.0% (Brazilian Solar Energy Atlas) and correlation of 0.98.

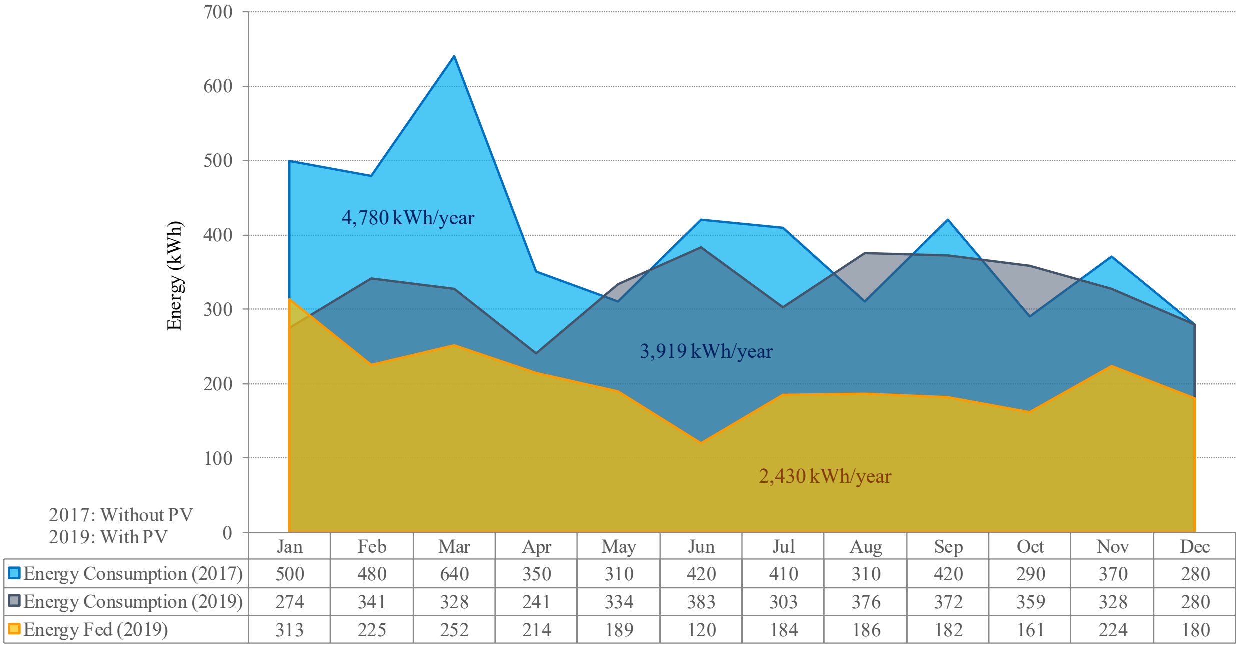
The results also show that the real performance of the PV system (measured PR) is lower in the months when the temperature is higher, which can be justified by the high temperature loss characteristic of crystalline silicon PV devices. The measured PR (2019) presented values larger than 80% in the months from January to September, reaching a peak of 94.1% (September) and a lower value of 76.3% (October).

The high values found for PR can be justified by good PV system design and engineering, a low Inverter Loading Ratio (ILR = 88%, from a 2.65 kWp PV array and 3 kW inverter), by the possible occurrence of overirradiances (ALMEIDA; ZILLES; LORENZO, 2014; DO NASCIMENTO et al., 2020; NASCIMENTO et al., 2019) at the PV system installation site (which increases its PV energy production for oversized inverters), and because the house has a white roof and a well ventilated PV system (MARTINS; MANTELLI; RÜTHER, 2022).

3.4.5 Consumption profiles at the PU

3.4.5.1 Utility’s perspective: Consumptions profiles and surplus electricity fed into the grid

Figure 3.12 shows the monthly evolution of electrical consumption of the case-study PU, obtained from electricity bills, before the PV system installation (light blue, upper region of the graph = period of 2017), and after the PV system installation (dark blue, central region of the graph = period of 2019) and the surplus energy fed into the electricity grid by PU (yellow, lower region of the graph = period of 2019).



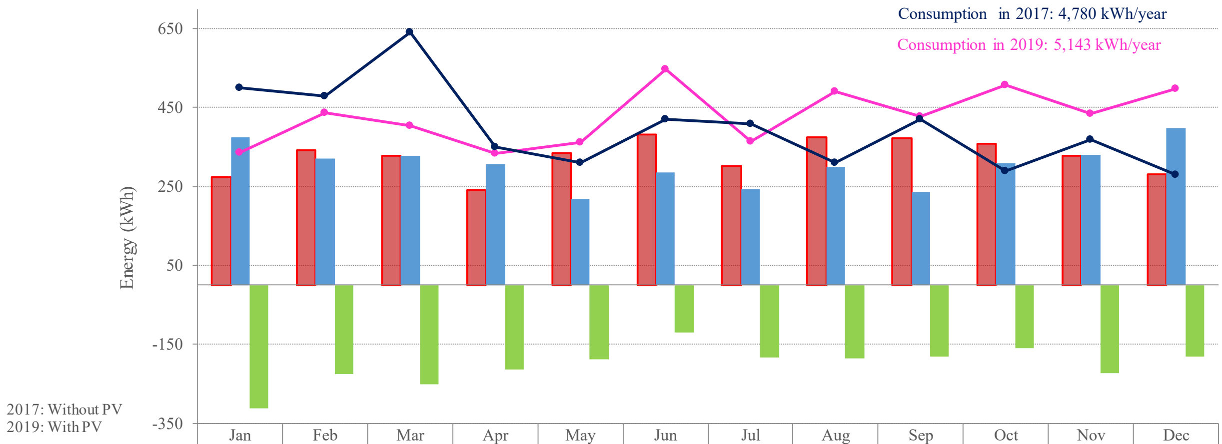
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
🟦 Energy Consumption (2017)	500	480	640	350	310	420	410	310	420	290	370	280
▩ Energy Consumption (2019)	274	341	328	241	334	383	303	376	372	359	328	280
🟧 Energy Fed (2019)	313	225	252	214	189	120	184	186	182	161	224	180

Figure 3.12. Consumption profiles and surplus electricity fed into the utility power grid by the case-study residential consumer previous (light blue, upper region of the graph = period of 2017), and after (dark blue, central region of the graph = period of 2019) the rooftop PV installation. The lower region of the graph (orange) shows the surplus energy fed into the electricity grid by PU in 2019.

From the distribution utility’s perspective, the results show that the annual consumption before the PV installation (Jan to Dec/2017) was 4,780 kWh/year. After the PV generation was installed (Jan to Dec/2019), the PU’s annual consumption was 3,319 kWh/year and the surplus active energy fed into the Utility grid (offset in 2019 on PU’s electricity bills) was 2,430 kWh/year. The adoption of PV solar energy in the house provided a consumption reduction of 18% (861 kWh), when we compare the electricity bills from years 2017 and 2019.

3.4.5.2 *Prosumer's perspective: Consumption profiles, PV generation and grid injection of surplus electricity*

Figure 3.13 shows the monthly evolution of the PU consumption before (Jan to Dec/2017, blue line), and after the PV installation (Jan to Dec/2019, pink line); of the excess PV energy fed into the power grid (Jan to Dec/2019, green bars); of the PV generation (Jan to Dec/2019, blue bars) produced by the PV system, and the electricity consumption from the utility grid (red bars).



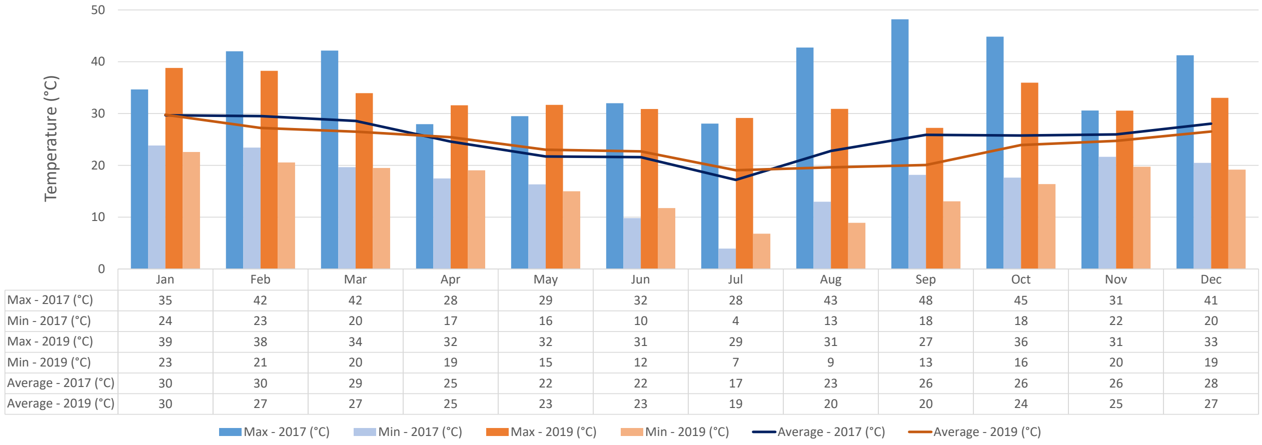
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
🟥 Utility Grid Consumption	274	341	328	241	334	383	303	376	372	359	328	280
🟦 PV Generation	375	322	328	308	217	285	244	300	237	310	331	398
🟩 Injected Energy	-313	-225	-252	-214	-189	-120	-184	-186	-182	-161	-224	-180
New Consumption (2019)	336	438	404	335	362	548	363	490	427	508	435	498
Old Consumption (2017)	500	480	640	350	310	420	410	310	420	290	370	280

Figure 3.13. Consumption profiles, PV generation and surplus electricity fed into the grid by the case-study residential PU.

The results show that before the PV system was installed (Jan to Dec/2017), the PU presented an annual electricity consumption of 4,780 kWh, fully supplied by the public utility grid. After the PV system was installed (Jan to Dec/2019), the PU presented a PV generation of 3,644 kWh (of which 2,430 kWh were fed into the utility's grid) and an electricity consumption from the grid of 3,919 kWh. The PU's total consumption was 5,143 kWh/year (3,319 kWh from the utility and 1,244 kWh from simultaneous PV generation (self-consumption)).

The results show, for the year 2019 and for the Summer months (Jan to Mar), a consumption reduction of 442 kWh (↓27.3%) compared to 2017. For the Autumn months (Apr to Jun), an increase of 165 kWh (↑15.3%). For the Winter months (July to Sept), an increase of 140 kWh (↑12.3%). For the Spring months (Oct to Dec), an increase of 501 kWh (↑53,3%).

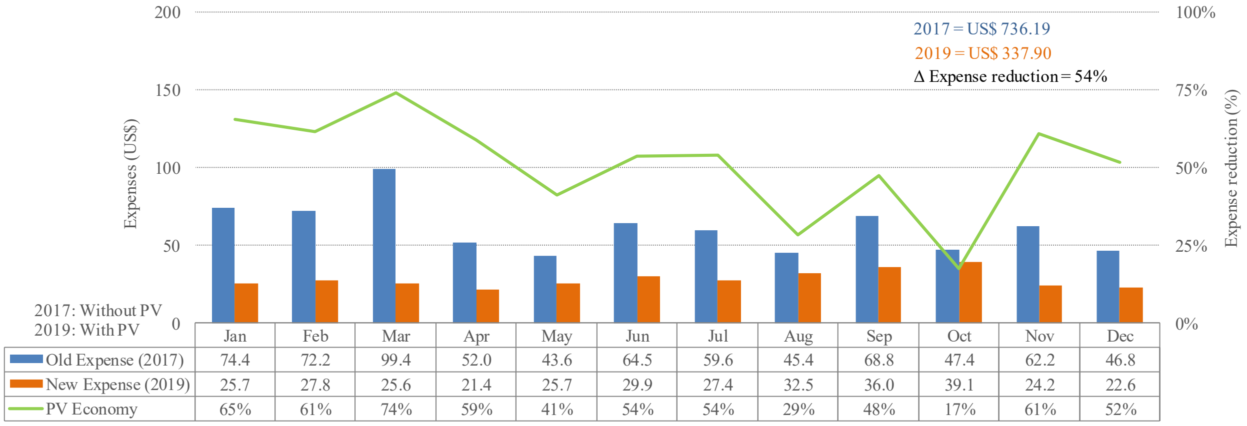
It was observed that after adoption of PV generation, the PU showed an increase in its total annual electricity consumption of 363 kWh (7.6%). The observed differences may have been caused by inter-seasonal temperature differences, by changing user habits, and by possible waste due to the greater supply of electricity. However, electricity consumption from the utility grid was reduced by 861 kWh (18%). To complement the graph in Figure 3.13, the maximum and minimum temperatures for each month, for the years 2017 and 2019, are presented in the graph of Figure 3.14.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max - 2017 (°C)	35	42	42	28	29	32	28	43	48	45	31	41
Min - 2017 (°C)	24	23	20	17	16	10	4	13	18	18	22	20
Max - 2019 (°C)	39	38	34	32	32	31	29	31	27	36	31	33
Min - 2019 (°C)	23	21	20	19	15	12	7	9	13	16	20	19
Average - 2017 (°C)	30	30	29	25	22	22	17	23	26	26	26	28
Average - 2019 (°C)	30	27	27	25	23	23	19	20	20	24	25	27

Figure 3.14. Maximum and minimum temperatures for each month, for the years 2017 and 2019, into the period of 8am to 6pm.

Figure 3.15 shows the expenses with electricity before and after the installation of solar PV generator and the percentage reduction of expenses on the PU’s electricity bill due to PV integration.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Old Expense (2017)	74.4	72.2	99.4	52.0	43.6	64.5	59.6	45.4	68.8	47.4	62.2	46.8
New Expense (2019)	25.7	27.8	25.6	21.4	25.7	29.9	27.4	32.5	36.0	39.1	24.2	22.6
PV Economy	65%	61%	74%	59%	41%	54%	54%	29%	48%	17%	61%	52%

Figure 3.15. Expenses with the electricity bill before and after the installation of a rooftop PV generator at the case-study house in Florianópolis, Brazil.

The calculations were made based on data from monthly electricity bills provided by the distribution utility. Although the consumer increased consumption by 7.6% (363 kWh), the annual expenditure on electricity from the utility decreased by US$ 398.3 (54%)

3.4.6 Financial analysis of Return on Investment - ROI

From the prosumer's perspective, the financial analysis of the PV system adoption was carried out by evaluating the ROI, the NPV and the IRR for different rates of return on capital. The rates of return on capital adopted in this paper correspond to real interest rates and, therefore, do not have built-in rates related to monetary correction or inflation (currency devaluation over time). The PV system has a useful life of 25 years, and the inverter has a useful life of 10 years. The total PV installation cost (module + inverter + installation cost) was US$ 4,673 turnkey. The annual cost of maintenance and operation of the PV system was 1% of the total PV system installed cost. The annual yield reduction adopted was 0.5% per year (DA FONSECA et al., 2020; JORDAN; KURTZ, 2013). In the cash flow, two investments of US$ 935 (inverter price) were considered for replacing the inverter in the years 10 and 20. Through the PU's electricity bills, unit energy costs were obtained as follows: (i) for consumption of up to 150 kWh, the average annual amount charged was 0.1459 US$/kWh; (ii) for consumption above 150 kWh, the average annual value was 0.1728 US$/kWh for the kWh in excess of the first 150 kWh. The monthly connection charge for this PU class is equivalent to 100 kWh/month (100 x 0.1459 = US$ 14.59).

Under the conditions analyzed, the PV generation (3,644 kWh/year) provided an annual benefit for the PU of US$ 583.15. Table 3.5 shows, from the prosumer's perspective, the evolution of the PV system's payback, NPV and IRR, considering different scenarios of Minimum Attractive Rate of Return (MARR) for two situations: (i) PV system with a 60% subsidy from the Utility (taking into account the CELESC PV Bonus program) and; (ii) PV system without subsidy (more typical scenario).

Table 3.5. Evolution of payback time, NPV and IRR considering different annual discount rates (MARR) for the roftop PV system considered in this work.

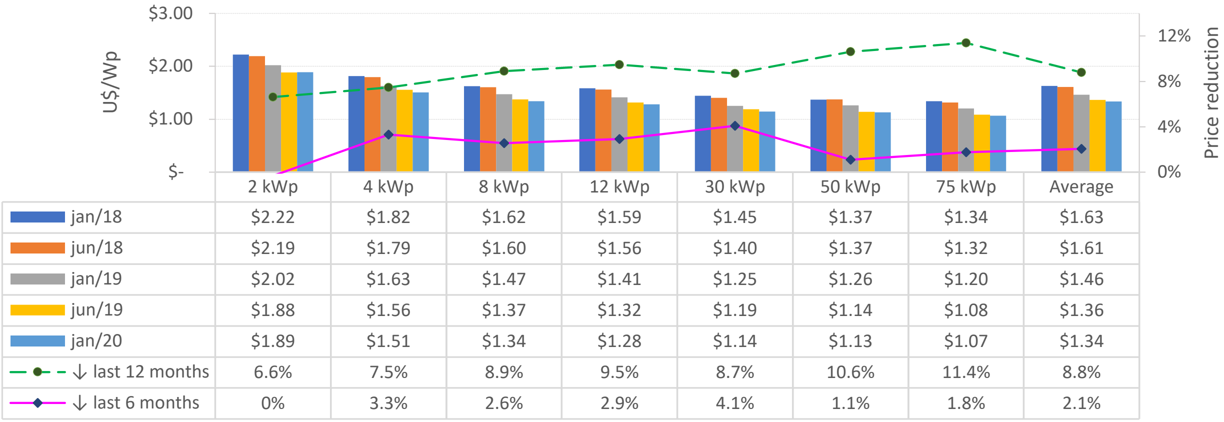
Financial indicators: PV installation with subsidy (CELESC PV Bonus Prices)					**Financial indicators: PV installation without subsidy (Market Prices)**				
MARR	**NVP** (US$)	**IRR**	**Payback** (years)	**LCOE** (US$/kWh)	**MARR**	**NVP** (US$)	**IRR**	**Payback** (years)	**LCOE** (US$/kWh)
0.0%	13,468.96	38%	2.6	0.11	0.0%	9,964.29	13%	6.7	0.17
0.5%	12,493.70	37%	2.6	0.11	0.5%	9,049.82	12%	6.9	0.17
1.0%	11,603.96	37%	2.6	0.11	1.0%	8,216.62	12%	7.0	0.18
1.5%	10,791.09	36%	2.6	0.11	1.5%	7,456.45	11%	7.2	0.18
2.0%	10,047.38	35%	2.7	0.11	2.0%	6,761.97	11%	7.3	0.19
2.5%	9,365.99	35%	2.7	0.12	2.5%	6,126.66	10%	7.5	0.19
3.0%	8,740.81	34%	2.7	0.12	3.0%	5,544.73	10%	7.6	0.20
3.5%	8,166.40	33%	2.7	0.12	3.5%	5,011.00	9%	7.8	0.21
4.0%	7,637.90	33%	2.8	0.12	4.0%	4,520.84	9%	8.0	0.21
4.5%	7,150.98	32%	2.8	0.12	4.5%	4,070.13	8%	8.2	0.21
5.0%	6,701.75	31%	2.8	0.12	5.0%	3,655.18	7%	8.4	0.22
5.5%	6,286.74	31%	2.8	0.12	5.5%	3,272.68	7%	10.0	0.23
6.0%	5,902.82	30%	2.9	0.13	6.0%	2,919.66	6%	10.3	0.23
6.5%	5,547.20	29%	2.9	0.13	6.5%	2,593.46	6%	10.6	0.24
7.0%	5,217.37	29%	2.9	0.13	7.0%	2,291.69	5%	10.9	0.25
7.5%	4,911.05	28%	3.0	0.13	7.5%	2,012.20	5%	11.3	0.26
8.0%	4,626.22	28%	3.0	0.13	8.0%	1,753.04	5%	11.7	0.26
8.5%	4,361.03	27%	3.0	0.14	8.5%	1,512.48	4%	12.1	0.27
9.0%	4,113.83	27%	3.0	0.14	9.0%	1,288.93	4%	12.6	0.27
9.5%	3,883.12	26%	3.1	0.14	9.5%	1,080.98	3%	13.2	0.28
10.0%	3,667.53	25%	3.1	0.14	10.0%	887.32	3%	13.9	0.29
10.5%	3,465.85	25%	3.1	0.15	10.5%	706.80	2%	14.6	0.30
11.0%	3,276.97	24%	3.2	0.15	11.0%	538.35	2%	15.6	0.31
11.5%	3,099.86	24%	3.2	0.15	11.5%	381.02	1%	16.7	0.31

The results show the economic viability for the installed PV rooftop systems, because the NPV > 0 until the 25th year, for all interest rates (0% to 11.5%), in both scenarios, with subsidy (CELESC PV bonus program) and without subsidy (Market Prices). For the IRR parameter, the subsidized scenario presents economic attractiveness for all interest rates, that is IRR > MARR, while the without subsidy scenario presented an economically attractive investment for interest rates ranging up to 5.5% and payback time of up to 10 years.

For the PV system without subsidy (real market conditions) the LCOE presented competitive values (ranging between 0.17 US$/kWh and 0.23 US$/kWh) compared to the tariffs charged by the utility for MARR up to 5.5%.

All the premises of this work meet the requirements of the current legislation, regulated by RN482 (ANEEL, 2012) and RN687 (ANEEL, 2015).

In the beginning of 2020, the Brazilian Consultancy Greener (GREENER, 2020) launched a strategic market study of distributed solar photovoltaic generation, interviewing 884 solar integrators in the period between December 19, 2019 and January 27, 2020. The research was sent to a wide range of companies across the country, with different sizes and experiences, thus obtaining a heterogeneous sample. The confidence level of the research is 95% with a 5% margin of error. Figure 3.16 shows the evolution of turnkey PV microgenerators prices (up to 75 kWp) for the end customer in Brazil.



	2 kWp	4 kWp	8 kWp	12 kWp	30 kWp	50 kWp	75 kWp	Average
jan/18	$2.22	$1.82	$1.62	$1.59	$1.45	$1.37	$1.34	$1.63
jun/18	$2.19	$1.79	$1.60	$1.56	$1.40	$1.37	$1.32	$1.61
jan/19	$2.02	$1.63	$1.47	$1.41	$1.25	$1.26	$1.20	$1.46
jun/19	$1.88	$1.56	$1.37	$1.32	$1.19	$1.14	$1.08	$1.36
jan/20	$1.89	$1.51	$1.34	$1.28	$1.14	$1.13	$1.07	$1.34
↓ last 12 months	6.6%	7.5%	8.9%	9.5%	8.7%	10.6%	11.4%	8.8%
↓ last 6 months	0%	3.3%	2.6%	2.9%	4.1%	1.1%	1.8%	2.1%

Figure 3.16. Prices evolution of PV rooftop systems for the end customer in Brazil. Source: (GREENER, 2020).

As seen in the graph in Figure 3.16, higher PV power systems tend to have greater price reductions than smaller systems.

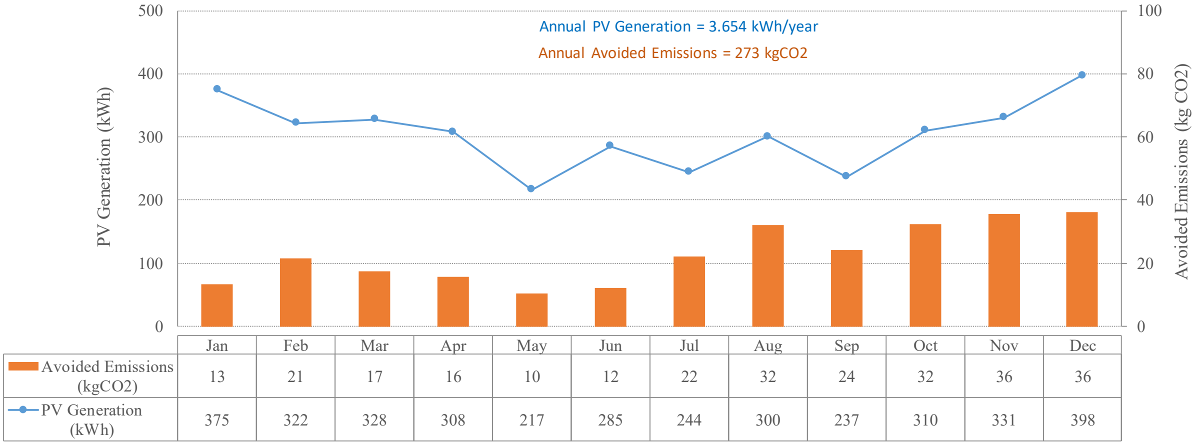
The results showed an average reduction of 8.8% in the last 12 months and 2.1% in the last six months. For PV systems up to 2kWp, the price reduction in the last 12 months was 6.6%, but in the last six months the price of installed Wp did not decrease. For PV systems up to 4kWp, which is the case of the system analyzed in this article, the price reduction in the last 12 months was 7.5% and for the last six months the price of the installed Wp showed a 3.3% decrease.

For a price reduction of 6.6% in the values presented in Table 3.5, there is economic viability, because the NPV > 0 until the 25th year, for all interest rates (0% to 11.5%), in both scenarios, with subsidy (CELESC PV Bonus Program) and without subsidy (Market Prices). For the IRR parameter, the scenario with subsidy showed economic attractiveness for all interest rates (IRR > MARR), while the without subsidy scenario presented an economically attractive investment for interest rates ranging up to 6.5% and payback time of up to 8.3 years. For a price reduction of 7.5%, there is also economic viability, for all interest rates, in both scenarios. For the IRR parameter, the scenario with subsidy showed economic attractiveness for all interest rates (IRR > MARR), while the without subsidy scenario presented an economically attractive investment for interest rates ranging up to 6.5% and payback time of up to eight years.

In the 1st half of 2021, a further strategic market research DG-PV was published (GREENER, 2021). The average PV prices from Jan/2020 to Jan/2021, for the end customer, increased 4.8% for PV microgenerators up to 75 kWp. In this case, the larger PV power systems suffered a larger price increase in the U$/Wp than the smaller ones. Further price increases, resulting from the coronavirus pandemic which is affecting markets throughout the world, are still under way.

3.4.7 Impacts on CO_2 emissions from the uptake of PV generation in the PU

Figure 3.17 shows the avoided CO_2 emissions ($kgCO_2$) (orange bars) and the PV generation (blue line), during the period from Jan to Dec/2019.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avoided Emissions (kgCO2)	13	21	17	16	10	12	22	32	24	32	36	36
PV Generation (kWh)	375	322	328	308	217	285	244	300	237	310	331	398

Figure 3.17. Monthly evolution of avoided CO_2 emissions in contrast to the PV generation.

The results show that the adoption of the PV generator provided avoided annual emissions of greenhouse effect gases to be released into the atmosphere of approximately 273 kg of CO_2 equivalent. In the period analyzed, the results show that the PU avoids an average of 1kg of CO_2 for every 13.4 kWh generated by the PV system. The modest values found for avoided CO_2 emissions can be justified by the fact that the Brazilian energy mix, unlike the situation in most other countries, is based mainly on renewable, low emission sources.

3.4.8 Comparative analysis between the individual PV rooftop case study and the average of PV households in the Florianópolis region, as well the theoretical values from the Brazilian Solar Energy Atlas.

Figure 3.18 shows, in boxplot form, the monthly and annual behavior of the distribution of measured energy yield values for the ensemble of 184 PV rooftops located in the Florianópolis city.

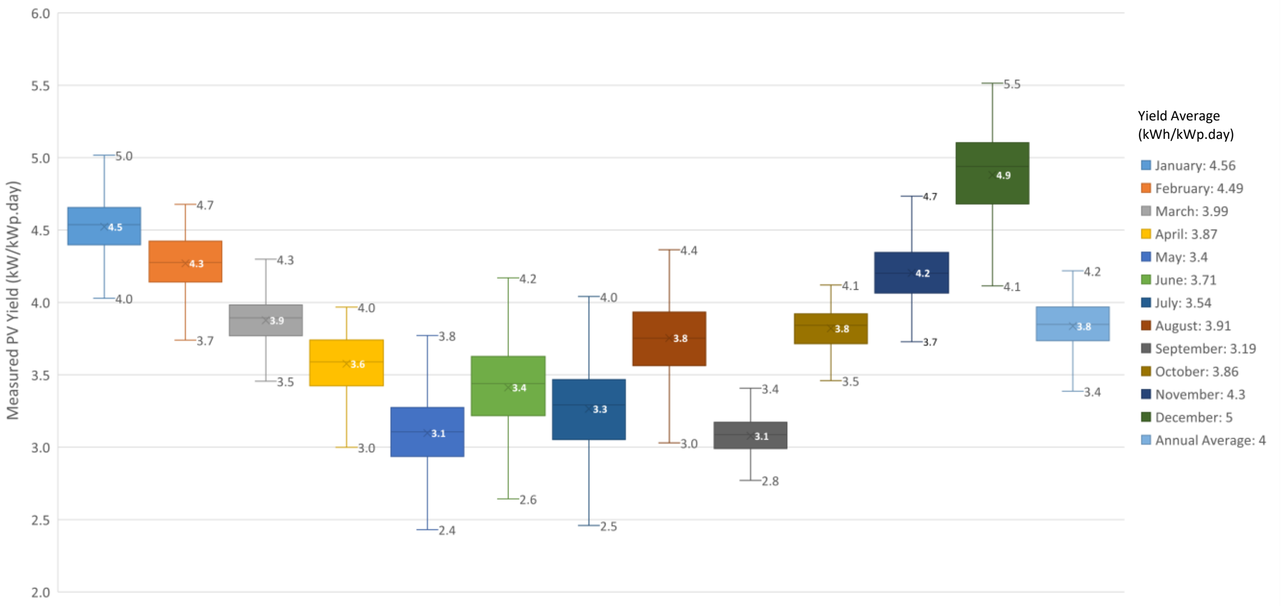


Figure 3.18. Measured PV daily energy yield for Jan-Dec/2019 and annual values in boxplot format.

Table 3.6 presents the statistical results and the number of each sample analyzed within the Florianópolis region, as well as a comparison of the average yield values measured with the average theoretical energy yield based on solar irradiation satellite data.

Table 3.6. Comparison between measured and theoretical energy yields for PV systems in Florianópolis, based on solar irradiation satellite data from the Brazilian Solar Energy Atlas.

Year 2019	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Number of elements	135	140	143	142	140	135	137	140	125	103	118	122	83
$\overline{X}$ Measured PV Yield (kWh/kWp.day)	4.52	4.27	3.88	3.58	3.10	3.41	3.26	3.75	3.08	3.82	4.20	4.88	3.84
Median of Measured PV Yield (kWh/kWp.day)	4.54	4.28	3.89	3.59	3.11	3.44	3.29	3.75	3.09	3.84	4.20	4.94	3.85
Max Value of Measured PV Yield (kWh/kWp.day)	4.56	4.30	3.91	3.61	3.14	3.46	3.32	3.80	3.10	3.85	4.24	4.93	3.87
Min Value of Measured PV Yield (kWh/kWp.day)	4.49	4.24	3.85	3.54	3.06	3.36	3.21	3.71	3.05	3.79	4.17	4.83	3.80
Error (95% confidence) (kWh/kWp.day)	0.04	0.03	0.03	0.03	0.04	0.05	0.05	0.04	0.02	0.03	0.04	0.05	0.04
Percentage variation (%)	0.8%	0.8%	0.8%	1.0%	1.4%	1.5%	1.6%	1.1%	0.7%	0.8%	0.9%	1.1%	1.0%
Determination coefficient (R^2)	99.0%	98.2%	98.1%	97.8%	99.6%	99.0%	98.6%	99.2%	98.6%	98.8%	99.4%	96.5%	98.6%
$\overline{X}$ Theoretical Yield (PR 80%) (kWh/kWp.day)	4.20	4.21	4.04	3.62	3.23	2.85	2.91	3.39	3.17	3.46	4.11	4.22	3.62
Δ% $\overline{X}$ Yield (Theoretical x Measured)	7.8%	1.3%	4.0%	1.3%	4.0%	19.8%	12.3%	10.9%	2.8%	10.5%	2.3%	15.6%	6.1%

Note that the average annual error of the sample was 1.0% and the biggest error was recorded in July, with 1.6% compared to the average value. The R^2 coefficient[11] was greater than 96.5% of a normal distribution compared to the sample distribution. The average annual energy yield of the sample was 3.84 kWh/kWp.day or 1,401.6 kWh/kWp.year. Over the months, the highest values were recorded in December (4.88 kWh/kWp.day or 151.28 kWh/kWp.month) and the lowest recorded in September (3.08 kWh/kWp.day or 92.4 kWh/kWp.month).

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[11] The coefficient R^2 is a mathematical formula, which compares the distribution of a sample with a normal distribution and expresses how well correlated these distributions are.

Figure 3.19 compares the average sample values of the systems in Florianópolis with the individual system chosen as a case-study in this article. Figure 3.19. also presents a comparison of the measured results with satellite data from the Brazilian Solar Energy Atlas (PEREIRA et al., 2017).

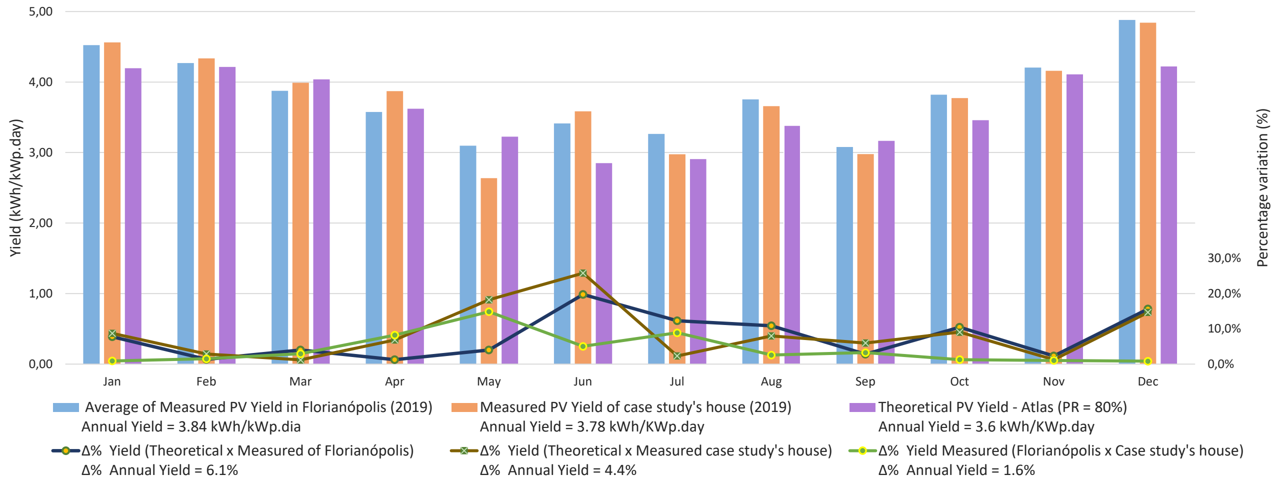

Figure 3.19. Comparative analysis between the individual PV rooftop case study and the average of PV households in the region, as well the theoretical values from the Brazilian Solar Energy Atlas (PEREIRA et al., 2017).

It is observed that when comparing the average of a significant number of PV systems close to the system analyzed in this article, it was possible to confirm that the PV generator is operating within the normal range for the region where it is located. The annual variation between the sample average and the house average is very close (1.6%); on a monthly basis, the variations showed low values (below 5%) for most months, except for the months of April (8.2%), May (14.9%) and July (8.0%) 2019. The statistical and comparative results justify the use of the house object of study in this research as a representative model for PV consumer homes in Florianópolis. It can be concluded that a small PV system, using multicrystalline silicon PV modules installed on a residential roof in this city will generate an average of 3.78 kWh/kWp.day or 1,379.7 kWh/kWp·year, for an annual global horizontal irradiation of 1,500 kWh/m^2·year at the site.

3.5 Conclusion

This paper presented a method to evaluate, from the distribution utility's perspective and from the prosumer's perspective, the technical-economic impacts provided by the adoption of rooftop solar PV generation in residential households. A case-study was presented for a household participating in the local utility's CELESC PV Bonus project, over a 12-month period (2019) evaluating all four seasons of a year. For the PV system analyzed, the results showed that the measured annual energy yield was higher than the expected annual yield based on the satellite values (1,379 kWh/kWp versus 1,315 kWh/kWp), with a difference of 4.8%, which lies well within the interannual variation of the solar radiation resource (PEREIRA et al., 2017). The results also showed that the real performance of the PV system (measured PR) is lower in the months when the temperature is higher, which can be justified by the high temperature loss characteristic of the crystalline silicon PV technology. The measured PR presented values larger than 80% in the months from January to September, reaching a peak of 94.1% (September) and a lower value of 76.3% (October). The high values found for PR can be justified by the oversizing of the inverter, by the possible occurrence of overirradiances at the location of the PV system installation (which increases its PV energy production), by the fact that the house has a white painted roof, and the PV system is installed in a high roof area with good ventilation.

From the distribution utility's perspective, the results showed that the annual consumption of the PU before the PV installation (Jan to Dec/2017) was 4,780 kWh/year. After the PV installation (Jan to Dec/2019), the PU's annual consumption was 3,919 kWh/year (18% reduction in consumption) and the surplus active energy fed into the utility's grid (offset in PU's electricity bills) was 2,430 kWh/year.

From the consumer's perspective, the results showed that the total annual consumption of the PU before the adoption of PV was 4,780 kWh/year, after the PV installation it was 5,143 kWh/year. After the CELESC PV Bonus project, the PU showed a 7.6% (363 kWh) increase in total annual electricity consumption, which can be traced back to a 2018-2019 hotter than usual summer in Florianopolis. However, the annual reduction in energy expenses in the utility bill was US$ 398.3 (54%).

It is observed that the adoption of PV generation provided a very modest annual avoided emission of Greenhouse Effect gases to be released into atmosphere of approximately 273 $kgCO_2$ per household. In the period analyzed, the results show that the PU avoids an average of 1kg of CO_2 for every 13.3 kWh generated by the CELESC PV Bonus solar system. Although the CO_2 emissions avoided per consumer unit are individually low, their great potential for reduction lies in the use of PV energy on a large scale, thus contributing to the reduction of the greenhouse effect.

The results show the economic viability for the installed PV rooftop systems, because the NPV > 0 until the 25th year, for all interest rates (0% to 11.5%), in both scenarios, with subsidy (CELESC PV bonus program) and without subsidy (Market Prices). For the IRR parameter, the subsidized scenario presents economic attractiveness for all interest rates, that is IRR > MARR, while the without subsidy scenario presented an economically attractive investment for interest rates ranging up to 5.5%. In addition, to the PV system without subsidy, the LCOE presented competitive values (ranging between 0.17 US$/kWh and 0.23 US$/kWh) compared to the tariffs charged by the utility for MARR up to 5.5%.

Based on the statistical and comparative analyzes presented in the results, it was possible to conclude that a small PV system, using traditional multicrystalline silicon PV modules installed on residential roofs in the city of Florianópolis, will generate an average of 3.78 kWh/kWp.day or 1,379 kWh/kWp.year, for an annual global horizontal irradiation of 1,500 kWh/m2.year at the site. This paper evaluated the role and benefits of solar prosumers in the context of distributed generation from both the utility and the consumer perspectives. The massive growth of small producers connecting to the electricity distribution grid is a new reality and generates a new paradigm that utilities must deal with. In this context, the results shown that is of utmost importance for utilities to start gathering operational data on grid-connected PV systems that will permeate more and more their distribution grids.

Finally, we concluded that the primary role of PV prosumer units is to reduce electricity costs for consumers, as well as to contribute to distributed generation in a decentralized and sustainable way. With distributed generation, the PV technology has become more accessible to small residential consumers, who today are the main users of this source in Brazil and worldwide.

4 GENERAL CONCLUSIONS

This thesis explored the potential of applying BI methodologies for managing and exploring data from a large sample of PV microgenerators. The method developed allowed the integration of several tools for data analysis, such as: platforms for remote operational data acquisition, algorithms for data treatment and validation, mapping tools with GIS technology, visualization platforms, and exploratory data analysis through dashboards. In this context, it was possible to define efficient indicators with an adequate theoretical background to support experts in PV-DG area for better decision-making based on technical and statistical data.

Based on the detailed documentation of the approaches used here and the results achieved, this thesis provides those interested in PV-DG area, which is booming in Brazil and worldwide, with a series of understandings and recommendations to assist in operational management, as well as in the safe and sustainable growth of the PV-DG market in the country. Thus, the goals of this work were achieved, and the main conclusions indicated below.

For the management of a large volume of PV generation data records transmitted through multiple distributed inverters, the use of BI, combined with the technical-statistical algorithm, provided a better exploration and analysis of these data, helping to support decision making in a quickly and well-founded way.

The maps plotted in GIS tools showed how each of the four regions that which the state of SC was divided (using the quartile method) behave because of the seasonality of solar irradiation. It was also possible to identify the location of each microgenerator and contrast the measured data with the theoretical yield expectation for each particular address. The results show annual differences between the average measured energy yield values and the theoretical average yield values of 0.3% (Range 1), 7.2% (Range 2), 3.7% (Range 3) and 0.7% (Range 4).

It was observed that the State of SC, in Southern Brazil, has minimum average yield values of 1.222 kWh/kWp·year (102 kWh/kWp·month) and maximum average values of 1,423 kWh/kWp·year (118 kWh/kWp·month).

The methodology developed in this research can be used to predict the monthly or annual generation of future PV systems to be installed anywhere in the state, Brazil, and the world, provided that the necessary information for the input data is available. Experts in the PV field can use the results obtained for the state of SC as reference graphs, with 95% reliability.

The tool developed in the first stage of the doctorate was also very useful to analyze a specific region of the state of SC, the island of Florianópolis, where a representative PV microgenerator was selected to be analyzed individually and to understand the behavior of the consumption and generation profile of single-family homes in SC, with a PV rooftop integrated into the building. This research presented, from the utility's perspective and from the prosumer's perspective, the technical-economic impacts provided by the adoption of solar PV generation.

The fact of having selected a representative prosumer of the sample of PV systems in the Florianopolis region, close to a solarimetric reference station and providing data of low uncertainty, allowed us to analyze with more property the PV household yield values contemplated by the PV bonus program. Based on the statistical and comparative analyzes presented in the results, it was possible to conclude that a small PV system, using traditional multicrystalline silicon PV modules installed on residential roofs in the city of Florianópolis, will generate an average of 3.78 kWh/kWp·day or 1,379 kWh/kWp·year, for an annual global horizontal irradiation of 1,500 kWh/m2·year at the site.

The high values found for PR can be justified by the oversizing of the inverter, by the possible occurrence of overradiances at the site of the PV system installation, by the fact that the residence has a white painted roof, and the PV system is installed in a high place with good ventilation, and by the possibility that the power supplied by the PV systems is greater than that informed by the manufacturer. It is also possible that the real losses of the PV system are smaller than those adopted in the simulations via PVsyst (3%).

This work allowed to evaluate the role and benefits of solar prosumers in the context of distributed generation from both the utility and the consumer perspectives. The massive growth of small producers connecting to the electricity distribution grid is a new reality and generates a new paradigm that utilities must deal with. In this context, the results shown that is of utmost importance for utilities to start gathering operational data on grid-connected PV systems that will permeate more and more their distribution grids.

From the distribution utility’s perspective, the results showed that, before the PV installation (Jan to Dec/2017), the PU’s annual consumption was 4,780 kWh/year. After the PV installation (Jan to Dec/2019), the PU’s annual consumption was 3,919 kWh/year (18% reduction in consumption) and the surplus active energy fed into the utility’s grid (offset in PU’s electricity bills) was 2,430 kWh/year.

From the consumer’s perspective, the results showed that, before the adoption of PV (Jan to Dec/2017), the PU’s total annual consumption was 4,780 kWh/year, and, after the PV installation (Jan to Dec/2019), it was 5,143 kWh/year. After the CELESC PV Bonus project, the PU showed a 7.6% (363 kWh) increase in total annual electricity consumption, which can be traced back to a 2018-2019 hotter than usual summer in Florianopolis. However, the annual reduction in energy expenses in the utility bill was US$ 398.3 (54%).

The results show the economic viability (NPV > 0 before the 25th operational year) for the installed PV rooftop systems, for all interest rates (0% to 11.5%), in both scenarios, with subsidy (CELESC PV bonus program) and without subsidy (Market Prices). For the IRR parameter, the subsidized scenario presents economic attractiveness (IRR > MARR) for all interest rates, while the without subsidy scenario presented an economically attractive investment for interest rates ranging up to 5.5%. In addition, to the PV system without subsidy, the LCOE presented competitive values (ranging between 0.17 US$/kWh and 0.23 US$/kWh) compared to the tariffs charged by the utility for MARR up to 5.5%.

The adoption of PV generation provided a very modest annual avoided emission of GEG to be released into atmosphere of approximately 273 $kgCO_2$ per household. In the period analyzed, the results show that the PU avoids an average of 1kg of CO_2 for every 13.3 kWh generated by the CELESC PV Bonus solar system. Although the CO_2 emissions avoided per consumer unit are individually low, their great potential for reduction lies in the use of PV energy on a large scale, thus contributing to the reduction of the greenhouse effect.

The primary role of PV prosumer units is to reduce electricity costs for consumers, as well as to contribute to distributed generation in a decentralized and sustainable way. With distributed generation, the PV technology has become more accessible to small residential consumers, who today are the main users of this source in Brazil and worldwide.

4.1 Limitations

This work had the following limitations, listed to allow better replication of the methodology in the future.

The collection of measured data was done for the period of one year (January to December). However, data from simulations based on historical series were used for sample validation. The data used for simulations and theoretical reference come from a free platform with satellite data, the Brazilian Solar Energy Atlas 2nd edition (PEREIRA et al., 2017), that despite presenting a large historical period of records, the distance between the georeferenced points with solar irradiation information is up to 10 km. For more accurate irradiation values at the exact point of the microgenerators, it would be necessary to install solarimetric sensors on each PV roof. However, in the performance analysis of the microgenerator representative of the sample of PV systems in the Florianópolis region, the average of reference data from a high resolution solarimetric station, located 800m away, for a period of 10 years was used (ANTONIOLLI et al., 2022; COLLE, 2007).

The access to real-time information was limited due to the implementation process of the new General Law for Personal Data Protection (LGPD), Law Nº 13,709/2018 (BRASIL, 2018). For reasons of legal insecurity, the project managers thought it prudent to restrict the access that was initially free, limiting it to only operational data of energy and power of the systems until the end of 2019.

The COVID-19 pandemic got in the way of the contact with CELESC and the cooperation process of the company with UFSC, making it unviable to analyze the consumption of the units contemplated by the PV Bonus. Furthermore, the consumption data for small consumers are made available by the utility only on a monthly basis. It does not exist for category B (low voltage), only for category A (medium voltage) consumers.

The results apply to Santa Catarina and Florianópolis, some variations are expected for other locations and other profiles of residential prosumers present in the country.

4.2 Recommendations for future developments

The evolution of the solar PV industry to date has been remarkable, with several milestones achieved in recent years in terms of installations, cost reduction and technological advances, as well as the creation of important solar energy associations. Clearly solar energy will be and will continue to be an essential renewable energy option in the coming decades. In Brazil, much of the DG comes from low and medium voltage connected PV plants, such as rooftop PV systems.

As well as PV rooftop systems, energy storage within the DG market has increased significantly in recent years (IRENA, 2019a, 2020), largely thanks to supportive policies, mainly net metering, tax incentives, and cost reduction. For example, behind-the-meter storage business models allow consumers to store electricity generated by the PV roof at times when the tariff is cheaper and consume it or sell it to the grid at times when the tariff is more expensive.

The novelties that have been emerging in the DG model lack auxiliary systems for operationalization, which indicates that new business models can emerge from the existing ones to meet new service demands. In countries where DG is more developed, such as Germany, the concept of virtual power plant (VPP) has emerged (NIKONOWICZ; MILEWSKI; WARSAW, 2012b; OTHMAN; HEGAZY; ABDELAZIZ, 2015). The VPPs interconnect real power plants, and for this reason are called virtual power plants, making the power generation branched into one big power plant and also allowing the proximity of generation and point of consumption, decreasing the costs with distribution (HERNÁNDEZ, 2015). The evolution of information technologies associated with the 4th industrial revolution and the digital age are transforming traditional industry, forcing it to change the paradigms of perception, production, and distribution of the capitalist world. Today, through the widespread deployment of sensors in the production environment, it is possible to unite the physical and virtual worlds (CARDOSO et al., 2017; PASQUALOTTO; BUBLITZ, 2017; SANTOS et al., 2018). Therefore, proposing a virtual power plant model is to seek a broad evolution and to spread, through the continuity of this research, a trend in the energy sector.

A single PV microgenerator generates large volumes of raw operational data, in the most varied time scales. When creating a PV Virtual Power Plant (PV-VPP) composed of hundreds or thousands of microgenerators, it is necessary to organize and store this data. In this context, great challenges arise. Among them, the integration and transformation of raw data into relevant information for the control, management, and decision-making process of these plants. For a better exploration and strategic analysis of data, the implementation of BI concepts to visualize and cross-reference the data extracted from different generation points makes a lot of sense, since wrong decisions can compromise the performance of these small plants. A simulation for the application of PV-VPP in the state of Santa Catarina was already done during the doctorate (ANTONIOLLI et al., 2020).

The South Australian government and Tesla are developing a grid of 50,000 solar PV household units connected to a VPP (ARENA, 2022). It is expected that VPP will meet about 20% of South Australia's average daily electricity demand (250 MW). In addition, the new plant is expected to reduce the amount charged on the energy bills of participating households by about 30% and benefit all South Australians with lower energy tariffs and greater energy stability (ARENA, 2022; IRENA, 2019b).

Given the limitations and opportunities highlighted by this work, some recommendations for future work are presented:

- Real-time monitoring of the data. The continuity of this research for the control and monitoring of the systems of the PV Bonus program could provide new knowledge and contributions to the market and to future research related to this subject, as well as evaluate the evolution of the project over the years.
- Compare the data from this research with other relevant information that allows for the creation of data-driven market intelligence.
- Automate statistical analysis to perform intelligent predictions through Machine Learning techniques.
- Map other Brazilian states or the entire country. The methodology developed allows the expansion of the study to other regions of the country. With the satellite data from the Brazilian Solar Energy Atlas, it is possible to create the maps by irradiation ranges, lacking only the data from the PV generators installed in the regions to be analyzed.
- Improve the dashboards and transform them into a commercial, interactive, and easily accessible tool for managers and decision-makers.
- Adapt the methodology for the information management of large PV solar power plants, aiming to optimize the control and access to information in real time and with pre-defined indicators according to the needs of managers, engineers, technicians, and investors.
- Explore the methodology and technology of Internet of Things (IoT) associated with DG systems and smart city concepts.
- Study shared generation models with storage systems using the households of the PV Bonus project.

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APPENDIX A – SHARED AUTHORSHIP AGREEMENT

All the co-authors of the two articles that comprise this thesis provided written consent to include them herein. The consents are presented in this Appendix.

Term of Agreement

This document attests that **Ricardo Rüther**, co-author of the following articles:

- *Development of technical and statistical algorithm using Business Intelligence tools for energy yield assessment of large rooftop photovoltaic system ensembles.*
  Published in Sustainable Energy Technologies and Assessments (ISSN: 2213-1388), volume 49, in February 2022, and catalogued through the DOI: doi.org/10.1016/j.seta.2021.101686

- *The role and benefits of residential rooftop photovoltaic prosumers in Brazil.*
  Published in Renewable Energy (ISSN: 0960-1481), volume 187, in March 2022, and catalogued through the DOI: doi.org/10.1016/j.renene.2022.01.072

AGREES with the use of these articles in the Doctoral thesis of Andrigo Filippo Gonçalves Antoniolli (first author), supervised by Professor Ricardo Rüther from the Graduate Program of Civil Engineering (PPGEC) at the Federal University of Santa Catarina (UFSC).

Florianópolis, June 30th, 2022.

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This document attests that **Helena Flávia Naspolini**, co-author of the following articles:

- *Development of technical and statistical algorithm using Business Intelligence tools for energy yield assessment of large rooftop photovoltaic system ensembles.*
  Published in Sustainable Energy Technologies and Assessments (ISSN: 2213-1388), volume 49, in February 2022, and catalogued through the DOI: doi.org/10.1016/j.seta.2021.101686
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- *Development of technical and statistical algorithm using Business Intelligence tools for energy yield assessment of large rooftop photovoltaic system ensembles*.
  Published in Sustainable Energy Technologies and Assessments (ISSN: 2213-1388), volume 49, in February 2022, and catalogued through the DOI: doi.org/10.1016/j.seta.2021.101686

- *The role and benefits of residential rooftop photovoltaic prosumers in Brazil.*
  Published in Renewable Energy (ISSN: 0960-1481), volume 187, in March 2022, and catalogued through the DOI: doi.org/10.1016/j.renene.2022.01.072

AGREES with the use of these articles in the Doctoral thesis of Andrigo Filippo Gonçalves Antoniolli (first author), supervised by Professor Ricardo Rüther from the Graduate Program of Civil Engineering (PPGEC) at the Federal University of Santa Catarina (UFSC).

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João Frederico de Abreu

APPENDIX B – PUBLICATIONS DURING THE DOCTORATE

1. LACCHINI, C.; ANTONIOLLI, A. F.; RÜTHER, R. The influence of different irradiation databases on the assessment of the return of capital invested in residential PV systems installed in different locations of the Brazilian territory. Solar Energy, v. 155, 2017.
2. ANTONIOLLI, A. et al. Análise de serviço de energia solar fotovoltaica compartilhada no brasil. Inovação, Tecnologia e Sustentabilidade - ITS 2017. Anais...2017
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4. ANTONIOLLI, A. F.; MONTENEGRO, A. DE A.; RÜTHER, R. ONIBUS ELÉTRICO ABASTECIDO POR EDIFICAÇÃO SOLAR FOTOVOLTAICA. XIV Encontro Nacional e X Encontro Latino-Americano de Conforto no Ambiente Construído (ENCAC/ELACAC). Anais...2017.
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7. ANTONIOLLI, A. F. et al. **PV virtual power plant: Evaluating the performance of clustered x individual rooftop PV installations**. Proceedings of the ISES Solar World Congress 2019 and IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2019, p. 1848–1856, 2020.
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9. DE ALBUQUERQUE MONTENEGRO, A.; ANTONIOLLI, A. F.; RÜTHER, R. Photovoltaic distributed generation in Brazil: Investment valuation for the 27 capital cities. Proceedings of the ISES Solar World Congress 2019 and IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2019, p. 1448–1456, 2020.
10. ZOMER, C. et al. Performance assessment of partially shaded building-integrated photovoltaic (BIPV) systems in a positive-energy solar energy laboratory building: Architecture perspectives. Solar Energy, v. 211, 2020.
11. ANTONIOLLI, A. F. et al. **Development of technical and statistical algorithm using Business Intelligence tools for energy yield assessment of large rooftop photovoltaic system ensembles.** Sustainable Energy Technologies and Assessments, v. 49, n. November 2021, 2022.
12. ANTONIOLLI, A. F. et al. **The role and benefits of residential rooftop photovoltaic prosumers in Brazil**. Renewable Energy, v. 187, p. 204–222, 2022.