Identifying Influential Factors Affecting the Shading of a Solar Panel

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***Abstract*—Photovoltaic (PV) systems produce less energy when operating under shadings. PV planners need to identify important factors affecting the shadings to forecast power generations in various ambient conditions. Using a case study, we show that overlooking the impact of an environmental factor, herein snowfalls, will result in overestimations in the power forecasting. In this paper, we study the context of the shading from different perspectives and introduce parameters that can affect the duration and severity of shading conditions. To identify key notions of the shading and important factors involved, we implement a literature review and include experts' knowledge by exploring PV planning tools and conducting a survey in the sector of solar energy. The identified factors can be used to develop a knowledge-based model representing key concepts associated with shading conditions. In addition, the identification of important factors affecting the duration and severity of shading conditions addresses new research domains that need to be explored in the field of PV shading and power estimation.**

Keywords—solar energy forecasting, PV planning, MPPT, partial shading, uniformly shading, PV power plant

I. INTRODUCTION

Since 25 years ago, solar energy has become one of the main contributors among other forms of renewable energy resources [1]. A photovoltaic (PV) system can be operated conveniently, requiring little maintenance. In Canada, the use of solar energy has been growing from 16.7 megawatts in 2005 to 3,040 megawatts in 2018 [2]. It means that consumers with minimum or basic knowledge about a solar panel have dealt with the process of PV system planning. However, the planning of an efficient system requires an expert's knowledge, especially when modules operate under shading conditions [3]. Shadings are caused due to various ambient terms such as adjacent buildings, trees, clouds, pollution, dust, and snow. Under the shadings, the performance of a solar panel is degraded significantly. In practical applications, maximum power point tracking (MPPT) control systems are utilized to overcome the problem of shading conditions [4]. Partially and uniformly shadings are the two scenarios recognized for shading terms.

Impacts of these two circumstances on PV performances have been studied in numerous papers by offering different MPPT approaches. The research endeavours aim to develop novel algorithms or hybrid methods assisting the PV system to operate in its maximum power point (MPP) when performing under uniform or partial shading conditions. A few focus on different characteristics of the shading in this context. Researchers' diverse backgrounds [5] and their non-technical point of views have produced an overwhelming amount of information in this topic [6, 7]. It is difficult to evaluate their results and practically utilize the proposed methods since dissimilar terminologies and research interests are applied in the papers. On the other hand, influential elements [8] that can affect the impact of shading have not been included in the studies. The rule of environmental factors and external parameters have been neglected even in most literature reviews, for instance [4, 8]. Impacts of a shading depend on the module type, fill factor, bypass diode placement, severity of shade, and string configuration [9]. The criteria for the accumulation of snow and ice on a panel relies on the characteristics of snowfall and also tilt angle of the panel, which cannot be mathematically modelled due to material complexity and ambient parameters [10, 11]. Further, it is argued that different types of snow and ice have unlike conductivity and thermal insulation [10]. In fact, the research context of PV shading entails meteorological data and environmental factors, requiring several knowledge domains.

During recent years, developing conceptual frameworks has grown significantly, allowing researchers to reuse and share information within interested communities [12]. Modelling disparate conceptual data from different domains implies using artificial intelligence, that involves semantics and computer processable languages [6, 13]. Semantic Web technologies offer software languages for representing knowledge-based models. In this work, using real data measured for a PV project, we show the negative effects of snowfalls on the system performances. We identify the important parameters that can influence shading and consequently the power productions. The notions and semantics associated with a shaded module are considered in four groups: I) its surface [9], II) the particle creating shading, III) the status of the ambient condition, and IV) the application and design of the PV system.

This paper is structured as follows: power productions are investigated using a case study. The main source of module shadings in most cases, snowfall, is considered for the study. The real power outputs of snow-covered panels are compared with the power estimations reported by a planning tool. In section III, the aim is to identify important concepts representing the knowledge-based of the shading in the PV domain. We perform a literature review about the shading and associated power reductions as well as including experts' concerns by conducting a survey. The key concepts and identified classes embodying module shadings are presented in section IV. In addition, several characteristics of the knowledge-based model, supposedly representing PV shadings, are defined in this section. The next step of developing the knowledge-based model is described in the conclusion, section V.

II. PV Power Productions under Shading Conditions

A. The Shading Phenomenon

A PV system is built in a series-parallel configuration to produce desired output power and voltage. In a practical application, they are connected in series to form a module of 36, 60, or 70 cells. Then the modules are assembled in different series and parallel configurations to form an array at the desired output voltage and current. For example, solar arrays are built in a fixed series-parallel configuration and the single module is equipped with bypass diodes included in different configurations. A bypass diode allows current from non-shaded parts of the module to pass by the shaded part and limits the effect of shading to the only neighboring group of cells protected by the same bypass diode [9, 14]. Partial or uniform shading conditions are the outcomes of shaded panels caused by buildings, trees, clouds, or various ambient conditions. Ambient conditions and environmental factors play a substantial part in the planning of a solar power generation due to the power efficiency reductions. For instance, in cold climates snowfalls play an important role in reducing energy production. Snow build-ups can reduce the output power of an array and result in performance degradation [10].

B. Planning a Solar Power Plant: Using a Case Study

We use System Advisor Model (SAM) to estimate energy productions and simulate a real PV power plant as a case study. NREL provides 9 PV case studies for which measured performance data are available for the community to be used [15]. The systems consist of three utility-scale (greater than 10 MW) systems and six commercial-scale systems (75-700 KW). Onsite measured snow data for the year 2012 can be used as inputs for these projects. One important advantage of using these PV systems is that if there is any system failure or an outage, it is reported in the project description provided by SAM [15].

We chose the Research Support Facility 2 (RSF2) building as the case study. It is a 408-kW PV system on the roof of the building located at Golden, CO. Its geographic information include latitude of 39.74° (N), longitude of 105.18° (W), and elevation of 1,829 (m). The measured power generations for the entire year of 2012 have been collected by SunPower [16]. AC powers were measured at each of the inverters and reported hourly in kilowatt-hour. The measured data, collected from the PV site, are publicly available to the PV community. The datasets related to the 9 PV case studies can be downloaded from SAM website [16]. We design the system using the SAM model. Table I depicts the sizing summary and an overview of the system (the complete simulation is available in [17]. Table I provides the PV system designed by the SAM model. Fig. 1 demonstrates the monthly power productions for months expecting snowfalls in 2012. To investigate the impacts of snowfalls on PV productions and comparing them with the actual powers [16]. As depicted in Fig. 1, the SAM model inaccurately estimates the energy generations especially for the three months of January, February, and December for the RSF2 project. Reviewing the snow data of the year 2012 reveals that there are substantial snowfalls for those months. It is argued that the snow-covered panels prevent the PV system from generate what the SAM software simulated.

TABLE I. Sizing Summary for the RSF2 Project

Technical Term	Value
Nameplate DC capacity	408.018 (kW_{dc})
Total AC capacity	500 (kW_{ac})
Number of inverters	2 (SMA America: SC250U-480V)
Number of modules	1,295 (SunPower SPR-315E-WHT-D)
Number of strings	185

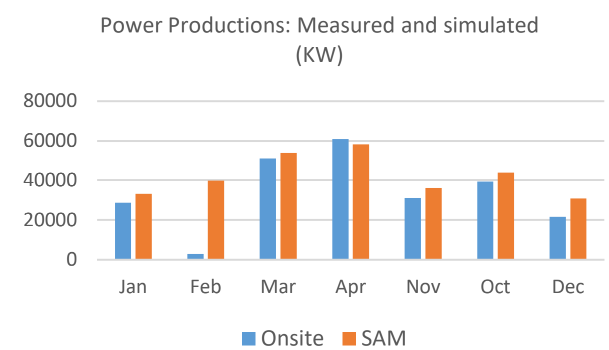

Fig. 1. Energy estimations reported by the SAM model and measured onsite for the RSF2 PV system, Golden, CO.

III. Identifying Important Classes

The Semantic Web, introduced by Berners-Lee [18], improves unstructured and/or semi-structured web pages and documents into a structured, well-defined and meaningful content of the web data. The need for a common framework that enables data sharing among a community has been the motivation behind the notion of the Semantic Web [19]. Ontology enables semantic relations among represented entities [20]. An ontology can be interpreted as formally describing a domain of interest through an abstract model [21]. In this manner, the community of a certain domain can reuse and develop the shared knowledge constructed with similar terminology. In fact, ontologies are agreements about sharing conceptualizations, containing conceptual frameworks for modeling knowledge and representation of a specific domain [22]. They provide a hierarchy of specified concepts in the form of classes [23]. An ontology model can: I) deal with large volumes of information and data, II) share knowledge and III) incorporate the relevant domain concepts and their associated relations [24].

To develop a knowledge representation model, we need to recognize key notions and semantics identifying important concepts of the subject matter. There are two main processes that ought to be undertaken in order to define essential classes and semantics for the knowledge representation model: I) literature review and II) collaboration with experts in the domain [25]. In this way, the model can be perceived as a reference model, as it contains major notions and concepts representing a specific knowledge area in the correlated domain.

A. Power degradations caused by Shadings

Performing a literature review about solar panel shadings and their impacts on PV power reductions helps to detect the concepts needed for the knowledge-based model. The severity and duration of shadings on a solar panel depends on: I) its surface [9], II) the particle creating shading, III) the status of the ambient condition, and IV) the application and design of the PV system. Semantics and notions related to these categories would be the main classes for the model. The severity and duration of a shaded panel can be decreased or increased depending on the existence of several factors. Therefore, the interactions of different parameters in these categories also can increase or decrease the impacts of a particular factor. They can exceed the negative effect of a factor when it applies individually.

Nevertheless, snowfall and dust are the main sources of solar power degradations in most cases [10]. Snowfall in cold climates is considered as the major reason for PV performance reductions [10, 11]. Solar modules receive less sunlight when the depth of snow is increased. In a full shading situation, there is no irradiance reaching the surface of a module and will result in zero power production. The type of the particle covering the surface of a solar panel also affects shading conditions. In a research [26], five typical elements of air pollution consisting of red soil, carbonaceous fly ash, sand calcium carbonate, and silica are investigated to assess their effects on the power efficiency. Chemical, biological, and electro-statistic effects of various airborne articles also affect PV performances and severity of shading in long term operations [26]. In addition, the property of a particle including its size, shape, and weight can influence the shading duration and severity. In the case of climate related particles such as snow and ice [10] their properties indicate the conditions of shadings and in result the output energy.

The role of the PV inclination is an essential aspect of the solar panel production as well, where snowfalls and particle aggregations on the surface of the panel are the main environmental concerns. The design of a PV system depends on the application and technical requirements of the project. Hence, panels with higher inclinations may experience less shading because of the snow shedding or especial maintenance considered for the project operation. The effects of several factors, involving airborne particles, climate related elements, and tilt angles, on PV performances are outlined in Table II.

TABLE II. THE EFFECT OF SHADINGS WITH DIFFERENT SOURCES ON PV PERFORMANCES

Particle	Effect on PV Performance
Dust and Sand	2-2.5% decrease of power (Turkey) [27]
Dust	50% reduction in the power for the panels exposed without cleaning for six months (Saudi Arabia) [28]
Sand	About 4% reduction in PV voltage [29]
Cement Dust	80% drop in PV short circuit voltage [30]
Red Soil	About 7% decrease in voltage [29]
Ash	25% PV voltage reduction [29]
Snow	Depending to the amount of snow and location, from 0.3-2.7% decrease in annual yield [31] to 1%-12% annual energy production losses [32]
Cloud	Depending on the location, experimented 77% reduction in power output [33]
Tilt Angle	**Effect on PV Performance**
25°	Power is 5.6% to 17.3% higher than 6° [34]
45°	17.4% energy loss per month for south-facing panels [35]
0°	18% losses in generation [36]
30°	Snow depth >1” cause 45% of daily loss [37]
40°	Snow depth >1” cause 26% of daily loss [37]
Dual Axis	Produce about 30% more electricity than the tilted system [38]

B. Investigating PV Planning Tools and Conducting a Survey

To include expert’s collaborations in the study, we investigated PV planning tools as well as online applications. Evaluating PV planning software/application products can help to find key parameters and concepts defining a shading condition. In addition, performing a survey to involve the community of solar energy was our attempt to perceive whether there is any consideration in the industry which was overlooked during the process of identifying important factors.

1) Exploring PV Planning Tools

A PV system planning tool, sometimes referred to and known as a designing tool, estimates the energy production and cost of solar plant projects. The accuracy of these data defines the correctness of power estimations, especially in locations where various environmental factors are involved. In addition to meteorological databases, the solar panel and inverter’s databases are needed for planning. There are online applications and software products freely available for the planning. They allow project managers, utility consumers, technology developers, and researchers to easily predict the electricity output of a system and evaluate a PV system performance. For the case of submitting a reliable planning software to be used as a case study later, 31 design related commercial and open-source PV software tools were nominated, using Google search. The level of accuracy and availability of their technical information were examined based on their help pages, technical references, manuals, software presentations, and demo videos as well as commercial emails received from the providers. The following bullets present criteria and overall considerations for the selection: I) Is a PV design or planning application included on the website? II) Is the trial version run and executed completely? III) How reliable and accurate were related databases and meteorological data? IV) What type of PV model is used in the simulation? V) What type of technical and scientific information are presented? In the second phase, we selected eight planning software as the most reliable planning tools including PVWatts, HOMER Pro, RETScreen, PVsys, SAM, Polysun, Solar Pro, PVSOL, and PV perform mod.

2) *The Survey*

We conducted a survey among members of the Canadian Solar Industries Association (CanSIA). The survey [39] was designed a questionnaire including three groups of questions concerning: 1) partial shading conditions (PSCs), 2) PV system modeling and simulation, and 3) MPPT approaches. Twenty-nine questions were prepared in total. A few participants, about 25, answered the questions and completed the survey. However, their comments and responses convinced us that the literature review and the self-assessment process of investigating PV planning tools fulfill our research objectives about including the important concepts of associate with the PV shading. After reviewing the responses, we found no new concept to add to the previous classes.

IV. Characteristics of the Knowledge-Based Model

Using Protégé and its plug-ins, we can design an ontology, as a knowledge-based mode, presenting the identified classes and their properties including data properties, object properties, and individuals. Individuals, also known as instances, can be referred to as being "instances of classes." Classes contain all the individuals that are categorized in a domain of interest. Classes may be organized into a superclass or subclass hierarchy, which is also known as a taxonomy. A class represents a concept in the domain or a collection of elements with similar properties. In an ontology model, properties describe attributes of instances of the class and relations to other instances. Object properties are relationships between two individuals, and data properties describe relationships between individuals and data values.

The outcome of the previous processes for identifying classes for a knowledge-based model will result in two super-classes, the shading and climate related factors. The location of a project indicates several features of the project containing its climate and geographic parameters. Interrelationships between different classes can be structured through the ontology model using Protégé. Figures 2 and 3 depict the main class axioms used for building the knowledge representative model.

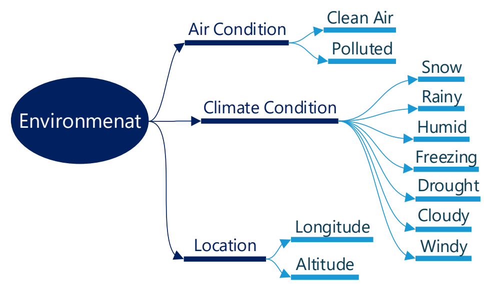

Fig. 2. Key factors concerning environmental elements

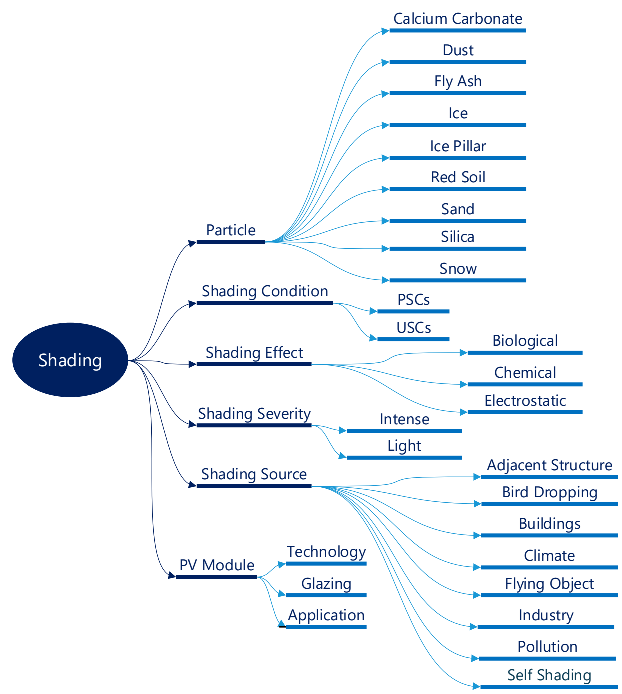

Fig. 3. Key semantic concepts concerning PV shadings

A. *The Result and Discussion*

To develop the knowledge base model, ontology reasoning and Semantic Web Rule Language (SWRL) are defined to infer information from the model. Now that the semantics of shading conditions have been included in the model, we can use a query language, for instance Semantic Query Enhanced Web Rule language (SQWRL), to extract information from the ontology. These rules can be utilized by other ontologies that deal with planning solar power plants and PV shading conditions.

Fig. 4 illustrates the graphical representation of the knowledge model built in Protégé. Specifying data properties, object properties, and instances of the knowledge representative model. It defines relationships of different factors with distinctive sources of several knowledge areas.

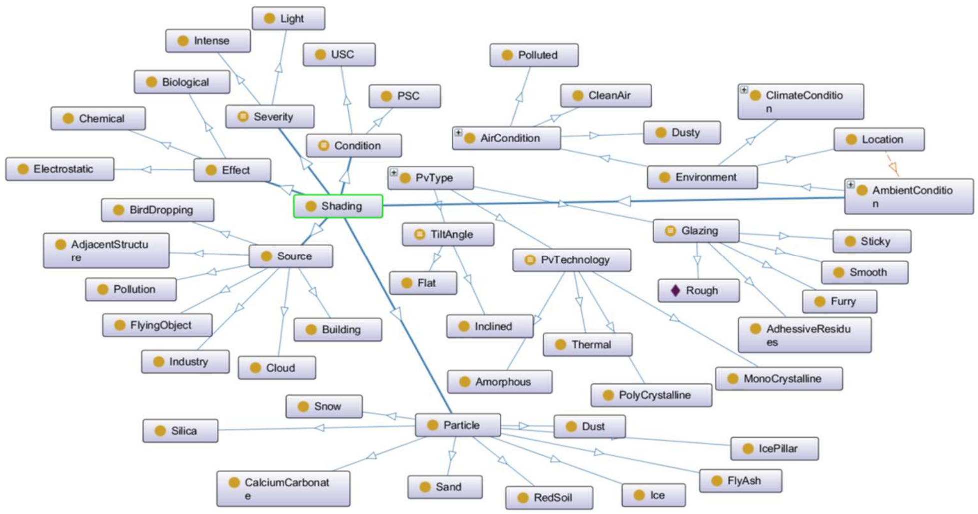

Fig. 4. The graphical representation for shading conditions and the related concepts in Protégé

In addition to the valuable information and data related to these influential factors, we can establish a rule-based system for the model indicating their associated power reductions. In fact, a set of rules determines correction factors that need to be applied to the hourly power estimations reported by the PV planning software. The graphical presentations provided by Protégé can be used for data visualization. In this manner, the model efficiently facilitates the process of the planning phase of a solar energy project by offering information required for managing the project from initial phase to closing.

V. Conclusion

In this work, an application of knowledge-based models in the solar sector is explored. Performing a literature review about the PV shading and searching PV planning tools as well as receiving comments from the practitioners in the industry allowed us to identify essential aspects about module shadings and system performances. We introduced the prominent factors into two main streams: I) shading and II) environment. The identified factors can influence the duration and severity of PV shadings, and consequently the system performances. They can be defined as super-classes in a knowledge-based model. Moreover, the model can be featured with SWRL allowing the system planner to extract information about power reductions caused by snow and several airborne particles including dust, cement, ash, red soil, calcium carbonate, and sand. The paper demonstrates how Semantic Web technologies enable us to improve knowledge representation, sharing, and reusing of relevant information generated by distinct sources.

An ontology model can be developed using a rule-based system, acting as a decision support system (DSS) to extract the designing and planning information about the impacts of shading conditions on power productions of a solar energy plant. In the future work, SWRL rules can be expanded based on power reductions caused by different shading sources. Therefore, there is a need for investigating the phenomenon of module shading concerning the identified classes introduced in this paper.

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