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Short Paper

Visual Monitoring of Photovoltaic Systems

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Abstract

We developed a scalable visual analytics framework for managing and analyzing hundreds of geographically distributed photovoltaic systems. These systems deliver performance parameters at different levels as well as environmental parameters. Our web-based framework gathers the data in a central server and allows comparisons of production values across time and photovoltaic systems, analysis of component failures and reporting errors. It is in daily use by a regional energy provider for over one year and its capabilities for fluent interaction and versatile configuration of visualizations from overviews to performance parameters of detailed components of individual systems are highly appreciated.

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [Computer Graphics]: User Interfaces—Graphical User Interfaces

1. Introduction and Related Work

Despite decreasing government funding in recent years, solar power is a forward-looking market and crucial towards the transition to renewable energy sources. More and more systems for generating power from solar energy are being built; not only does this include huge solar parks scattered throughout the landscape that contain hundreds or thousands of panels, but also smaller ones on individual houses seem profitable.

Monitoring these systems is of the utmost importance since it costs a substantial amount of money every single time they are out of order. Unfortunately no standard interface or protocol exists for such a task. Each vendor has its own solution which is usually a basic web application showing only the data of a single system and lacking data exploration, hierarchical abstractions, and means to compare the data against other systems or time periods. For example, *fronius* [Fro] only shows power values of a single system without providing any hierarchical insights or displaying time periods other than the day before. *solar-log* [Sola] provides different views starting from a dashboard where most information is shown as icons for a single system such as produced power, saved CO2 weight, or weather forecast. Comparisons between time and/or systems are not possible and the selection of a specific time interval is cumbersome. The strength of *solaredge* [Solb] is an overview of the solar panels which allows one to identify problems inside the system. However, it is limited when it comes to the visualization of detailed data and comparisons between systems or time periods.

In collaboration with a regional energy supplier, we developed a versatile and scalable solution for managing hundreds of photovoltaic systems consisting of components from different vendors. The visualization framework is capable of showing all present and past operational data for analyzing failures and errors, gathering and aggregating data from various sites, and performing comparisons across time and systems. The most relevant parameters are recorded every 5 minutes and pushed onto a central server each night. The data is also hierarchical by nature since all the components that a single system consists of are hooked up that way (Figure 1) and, additionally, each one is geo-referenced and assigned to a district that belong to a particular region or state.

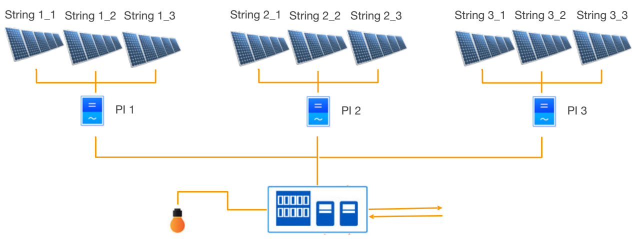

Figure 1: *A photovoltaic system. A string is a collection of solar panels. Strings provide DC current to their power inverter, which converts it to AC that is bundled within and fed into the public grid.*

Currently there are about 120 active systems maintained by our collaboration partner totaling more than 10.00 MWp. Altogether, there are nearly 600 power inverters from 12 different vendors installed. The range varies from 1 inverter per system to 110, whereas 90% of all systems on the platform only have 5 or fewer inverters installed – the majority of them have two or less installed. These are mostly roof systems with only a small area available to generate solar power. However, some open-space systems exist: the biggest one consists of 110 installed inverters with an overall peak power of 1.8 MWp. The number of solar panels that are attached to a power inverter is usually 8. Further details of such a system can be seen in Figure 1. Our main contributions are:

- A versatile navigation tool intended for interactive temporal exploration and comparison within and across time intervals.
- Various means for aggregating and depicting temporal information of the given hierarchies, as well as providing appropriate transitions between them.

Our web-based visual analytics application for monitoring and analyzing a large number and variety of photovoltaic systems is highly appreciated by our collaboration partner where it has been in productive use every day for over a year.

2. Visual Concept

The general requirements were to cover all systems at different aggregation levels from the most detailed information of each string to the entire system and even further up to district and state level. Immediate access to the respective information level was needed even though a web-based interface was required. A variety of comparisons of data across different stations and across time, which should be set up easily in an interactive way, was asked for as well as appropriate visualization techniques for revealing outliers and similarities. The development followed a user-centered design approach along with experts from the company who evaluated the system on a regular basis and prioritized further developments.

Figure 2: *The welcome screen showing the map.*

The design follows a coordinated multi-view approach extended by special full screen (maximized) modi that all views are capable of. Each view contains one to many diagrams as well as auxiliary components such as labels, checkboxes, and so on. The welcome screen is a maximized map view visually reporting whether business is usual or if any incidents happened the day before; depicted either in the map view (Figure 2) or in a separate table of incidents that contains more details. spikes express the yield of the systems visually in the map as so-called standard sun hours or as work. Although spikes are not ideal with respect to estimating heights (see Skau et al. [SHK15]) embedded in a map and exaggerated by color (see Cage [Cag]), they provide a distinctive and appealing display. The map view can be transformed for a more precise look to an advanced interactive bar graph (see Figure 3) that makes it easy to compare all yields of the day before (or any other time period). Static and adjustable horizontal helper lines support comparisons between multiple, as well as focus+context, aids in investigating single or adjacent sites. Any striking behavior of one or more systems appearing in the initial overview must be investigated further in the regular view of the application (see Figure 4). Transitioned to its normal size, the map serves as an auxiliary widget showing the locations of the systems that have been selected (see Figure 4 A).

The core feature is a navigation tool (Figure 4, center) for arbitrarily exploring temporal aspects either ”vertically” (D) by switching between different granularities of time periods (daily, weekly, monthly, or annually) or ”horizontally” (C) by moving along the chosen or given interval length. The navigation tool is designed to handle diagrams for single structures such as systems, a power converter, or a single string but also depicts these in their inherent hierarchy or even compares multiple units somewhere in our hierarchy. These abilities were crucial to our collaboration partner. It affects the time periods of each view, each diagram (see Figure 4), and even the elements of a diagram (such as different systems in Figure 5); either globally (for all open views and diagrams at once) or locally (for every chart or element individually) which results in necessary flexibility for comparisons. Simply by clicking or moving, the current date can be shifted in a vertical or horizontal direction which entails an immediate animated transition of all diagrams towards the aimed time period (Figure 4). Furthermore, the elements within a diagram can be individually shifted using the local navigation tool each has in relation to the global time (Figure 5). Maintaining the time difference between local and global time periods while changing the global time period is also possible. The requirements regarding the depiction of temporal information embedded in in our hierarchy were quite vague up to contradictory. Therefore we support different visualizations established in the community such as Line and Area Charts, Stacked Graphs (see Byron [BW08] or Heer [HBO10], Figure 6) and Braided Graphs (see Javed et al. [JME10], Figure 5). Each one of those can be easily morphed into one another or split up as Small Multiples (see Figure 8) by appropriate animated transitions. The hierarchical information referencing the depicted elements is encoded as a tree on the left (see Figure 9) or/and in the visualization itself; for example by Stacked Graphs (Figure 6). Accordingly, we provide different color mappings, either mapping the values of a diagram (for example DC or AC in Figure 4) or elements of the hierarchy to colors such as photovoltaic systems themselves in Figure 5 or power inverters of a single system in Figure 6.

Visual aggregation techniques like Stacked Graphs scale very well in our hierarchy with less than 10 children per node; however, they did not scale very well for the top level with over 100 systems. Thus, maximizing the system list provides a (pseudo) pixel-based visualization (see Sips [KSS06] and Keim [Kei00]) comparing all systems over the entire year (Figure 7).

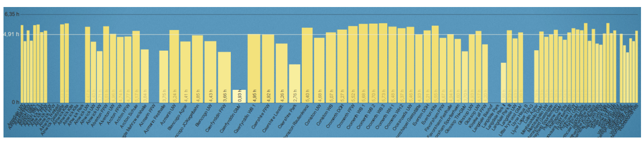

Figure 3: *The welcome screen showing advanced bar graphs.*

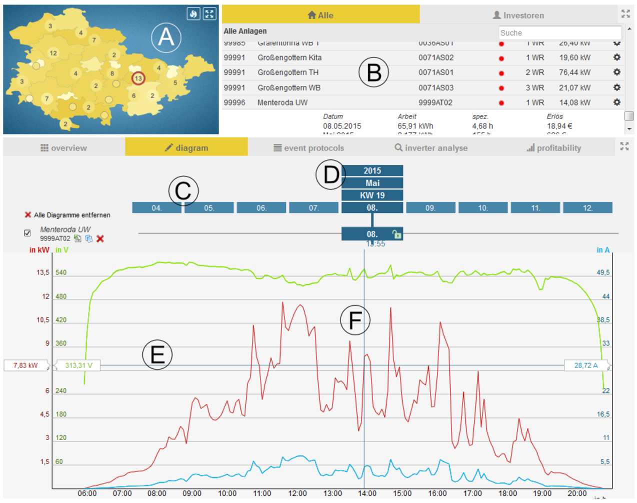

Figure 4: *Coordinated multi-views with map (A) and list of systems (B). The time navigation tool (C,D) presents the most important operational data below for a single system encoded in different colors combined in one diagram. The helper lines (E,F) aid the orientation and reveal the respective values for power AC (red), voltage DC (green), and DC itself (blue).*

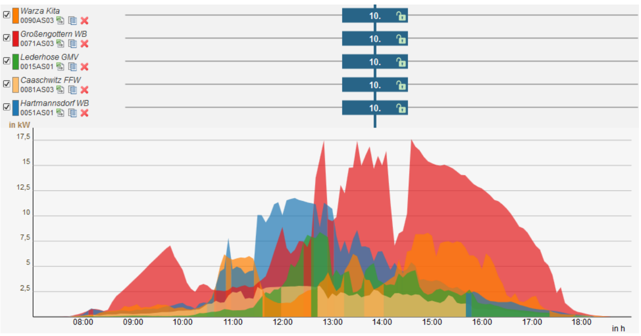

Figure 5: *Braided Graph of different systems.*

3. Implementation Details

Persistence is provided with MySQL. Currently, for about 100 systems, the data accumulates to less than 10GByte over an entire year. Some of the data (less than 100 MByte) is pre-aggregated for faster access. Our caching idea is simple, yet efficient, following the structure of our time navigation tool. All that could be reached vertically or horizontally on the current screen is pre-fetched. The data itself is cached on the client side in a data manager that stores all data of a session following the given hierarchy in storing the values for each year, month, week, day and timestamp. So if any information is needed, the data manager first checks if the data is present already and only loads it via Ajax if necessary.

4. Findings and Expert Review

As mentioned, the system has already been in production for over a year. It superseded all prior in-house and commercial applications and serves now as central application for monitoring and maintaining over 110 solar power systems. The visualizations are used more and more frequently for reporting details, issues, and success to the management and also to customers whose power systems are taken care of.

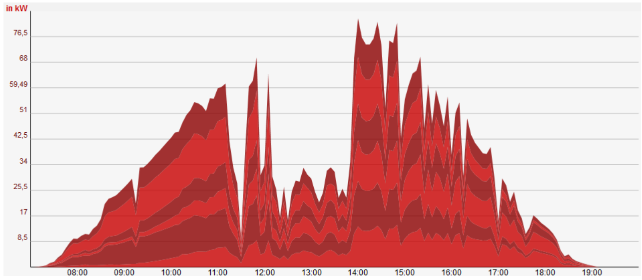

Figure 6: *All inverters of a system visually accumulated with alternating colors.*

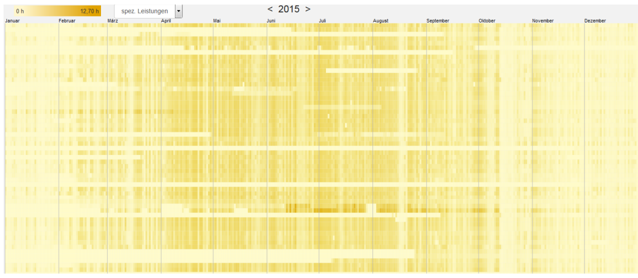

Figure 7: *The maximized view of the system list provides a (pseudo) pixel-based insight into the entire year. One can clearly see the two best performing systems. It was not very clear what makes this location so exceptional though. A deeper analysis with our framework later on revealed that data files sent by the power inverters were corrupt.*

We performed an extensive interview with the head of the monitoring and maintenance group who has been using the tool on a daily basis for over a year. In fact, starting the web browser and logging in to see whether or not all solar panels performed well the day before is his first task every day. If failures occurred he is notified on the start screen map or in a failure list. This capability appears simple, yet it improved his workflow dramatically since it spares him hours of logging in and out and repeatedly copying and comparing information from third party webpages from different vendors and manufacturers (each with a respective account per individual installation) in an Excel sheet. It is very fair to say that he was really grateful for what we have achieved so far.

We observed how fluently he operates the navigation tool to get to the systems of interest he wanted to show us. Comparing the power inverters of a single system is a common task especially if one of them reported a failure. Overlaying the charts of the power inverters and the entire system in one diagram revealed multiple times that the power inverters of a certain vendor operates as expected but reports the wrong data to the server. Another typical task was to distinguish whether or not systems near each other behaved very differently. Starting with Small Multiples to investigate the differences, we then went down to the inverter level of both systems (see Figure 8) and integrated them into one diagram (Figure 9) which revealed unusual development of inverters of the same vendor in the afternoon. At first the vendor denied the abnormal behavior, arguing this steep slope as regular, but, had to admit irregularity eventually after being confronted with the charts containing inverters from other vendors. Maybe our partners could have reached the same conclusion with their prior tools; however, never in less than two minutes time.

Another minor finding was that switching between different color mappings (either expressing different parameters or expressing different systems/inverters) seems to be no problem at all (at least for the head of the group who frequently changes it according to the situation). We were worried that this might be confusing to the users; however, there is currently not enough data (especially from the investor users) to confirm this conclusively.

The (pseudo) pixel-based view depicting all systems over an entire year was previously unknown to our experts. Although not used every day, the experts very much appreciated the annual overview for analyzing periodical patterns and outliers (see warm period around October 14th in Figure 7), ranking their performances, and comparing pilot systems to the regular ones and reporting the findings in discussion with the management.

5. Conclusion and Future Work

In this paper we presented a web-based application that originally started as a monitoring and visual analytics tool coping with time-varying, hierarchical, and geo-referenced data from about one hundred solar power systems. It later matured into a full-flavored monitoring and maintenance system that now includes features such as customer management for enabling customer-specific filters that allows insight only into their respective installations, PDF reporting and status updates, providing web forms for on-site inspection, versatile export capabilities for Excel, and, currently in development, financial planning and revenue calculation for individual systems.

Future work is going to focus on scalability and further refined visual analysis techniques. The number of systems is expected to grow by a factor of 10 within the next year, meaning more than a thousand photovoltaic systems need to be monitored. Progress in web technology might help us, but a lot of challenges regarding data management, level-of-detail representations, and semantic aggregation remain. It is also expected that live monitoring will become an option in the near future, which leads to further challenges of integrating the streaming data into the visual displays in a consistent and non-disturbing way.

Figure 8: *The voltage of the lower power inverters reveal abnormal flanks in the afternoon.*

Figure 9: *The inverter curves integrated in one diagram allows a more precise comparison.*

Acknowledgements

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