CAN ROBOTICS IN PV PLANT MAINTENANCE DEVELOP QUICKLY ENOUGH FOR THE SET ROADMAP?

Florin Popescu[1] and Stefan Wendlandt[2]
[1] Fraunhofer FOKUS, Kaiserin-Augusta-Allee 31, D-10589 Berlin, Germany,
Phone: +49 (30) 34 63 70-00, mail: florin.popescu@fokus.fraunhofer.de
[2] PI Photovoltaik-Institut Berlin AG, Wrangelstr. 100, D-10997 Berlin, Germany
Phone: +49 (30) 814 52 64-0, e-mail: wendlandt@pi-berlin.com

ABSTRACT:

In this study we address the issue of whether the field of robotics can supply the necessary technology readiness level (TRL) growth necessary to address the EU's Strategic Energy Technology (SET) roadmap targets for maintenance cost reductions in PV plants. The SET is a stakeholder-driven roadmap which shapes EU policy on, among others, PV sector growth, including measurable targets for performance, risk management and cost containment in different categories, including aspects of maintenance such as cost of diagnostics / failure analysis and quality control, lifetime and yield over lifetime. In the European context, with relatively rigid labor markets placing an inherent premium on night-time operations, 24-hour O&M automation is likely to play a leading role in meeting these targets. Moreover, in a global context robots can offer intensive maintenance in inhospitable and remote environments, where robot teams may integrate both multi-modal sensing and repair/cleaning action. We therefore investigate different maintenance needs and related actions, their relative frequency vs. age of installation and TRL levels of robotic solutions for each of these, where applicable, along with a prognosticated timetable of TRL / market penetration increases in each category the SET roadmap over the 5-10 year horizon.

Keywords: maintenance, robotics

1 INTRODUCTION

Photovoltaic (PV) based solar energy is unique among renewable energy sources as it is potentially scalable to meet the entire global energy demand (unlike, for example, hydroelectric power), currently has nearly double the lifespan, is much more recyclable (≥ 80% [1]), poses far less danger to its surroundings than wind turbines and is also quiet and not aesthetically obtrusive [2]. On the other hand, its power density is relatively small and requires active repair and cleaning in order to keep high performance for extended lifespans (40-50 years). Once the basic infrastructure has been set up (the rent for land use, the support structures, the electrical equipment), its unique advantage is that it is a sum of potentially tens of thousands of identical parts (modules), none of which are moving, having low overall system complexity and requiring no rare metals or minerals, while benefiting from economies of scale in production and in supply of its replacement parts. However, the sheer size of large PV plants, spread over multiple hectares, means that cleaning, inspection and repair are quite costly if they are to rely on human labor alone.

Despite recent and continuing advances in PV panel production cost, performance ratio in the field, and improved mounting stability and life-cycle, the basic physics of PV and direct solar irradiation still mean relatively low power density (per sq. km and per kg of installation), with basic economics - given variable climate of installation - remaining roughly on par with alternative sources in per kWh produced. Furthermore solar energy is is naturally aligned with consumption peaks in the grid. A well maintained plant would spend wisely on maintenance and repair, such that such expenditures bear a good return on investment in recovered production capacity. As PV panels are exposed to solar radiation, and convert energy types, it is natural that they should wear out with time - converting less and less of the incident light into electricity. A typical Performance Ratio (PR) value of a new system is between 0.8 and 0.9. Assuming degradation rates of 0.5 to 1% per year, at mid-lifecycle a loss of ca. 10% may occur (possibly eroding the profit margin). At some further point in time - we don't know exactly how long because no industrial scale PV plants have existed long enough - the electricity produced might be worth less than the minimal O&M cost (land rent), going from break-even to a net loss. Therefore maintenance is necessary even while assuming inverters, wiring and support structures do not also fail. However, basic risk mitigation demands that critical components are inspected and maintained - meaning a well planned maintenance trip can include several different tasks.

Insofar as panel replacement, it is important to note that not all PV panels degrade at the same speed. A better alternative than wholesale refurbishment near mid-lifecycle would be to replace only defect - or soon to become defect - panels. This doesn't only mean replacement but upgrade to newer, more efficient panel designs, reusing - insofar as possible - existing support structures and electrical hardware. However, there is currently no (cheap) means of automatically detecting which panels are defect outside of inspection in the field. Periodic cleaning is also necessary - not only to maintain higher performance ratio (on the order of 10% [3],[4]) but to prevent accelerated damage to the entire structure,

The basic economics of PV, determined by low power density, imply that inspection (passing by and inspecting 1K to 100K panels), cleaning (wiping each of these), repair and replacement (walking up to and servicing, let's say, 1/100 of the panels on the field), if done by humans, is prohibitively expensive, requiring potentially hundreds of thousands of man-hours. Furthermore most of the work should be done at night - some of it in inhospitable environments (e.g. deserts). Robots can work 24hours and can be built for resilience in tough environments. Even if maintenance is seldom performed, only automation can offer sensible enough economics at these scales. It comes as no surprise that robots (mostly for inspection and cleaning of PV panels) have already entered the market. The niche market (it doesn't even have its own ISO/IFR designation [10]) for service robots of interest in this paper, compared to the overall market for robots, places a sharp penalty on unit cost, because of the stringent economics aforementioned. Drones benefit from prior R&D expenditure and have been adopted to this purpose. Cleaning robots (or machines) have on the other hand been specifically developed, and have proven so far to be worth the expenditure and providing robust market actors [5], [6].

However, existing robots are limited in their autonomy either needing to be physically mounted or, in the case of drones, needing to be frequently recharged or even piloted. The implications of limited autonomy are compensatory human labor requirements. The reasons for this limitation are multiple: safety (an issue whose severity increases with autonomy and power), lack of high power high energy density power sources available and cost. The more autonomous a robot, the more jobs it can do, but also the more expensive it is. These limitations are all technological in nature, and their finding a way to market depends on R&D, or in other words, an increase in the Technological Readiness Level (TRL) REF of different robots types.

Since robots are highly R&D intensive, and since they are (by definition) flexible in the type of jobs they do, it is not to be expected that the PV industry itself shall bear the brunt of this expenditure. As has happened with industrial robots from their 'dawn' in the 1970s, and service robots since then, it is governmental funding agencies that drive robotics R&D development. Not only research funding, but important work in standardization and regulatory clarity, can only be carried out by national and super-national structures. It is for this purpose that we examine, in the paper, the EU's Strategic Energy Technology (SET) Plan [11], a specific set of goals and guideline to technological development in the short- to mid-term future, implying a set of funding targets which depend on measurable performance and market achievements. Our question is: can the SET goals, insofar as they pertain to PV O&M be met without further support and intervention, or do they require further investment and where?

In summary, the following O&M strategies that can benefit from (robotic) automation

- quality control at delivery
- failure and degradation analysis / inspection
- cleaning
- service, component replacement and repair
- upgrade to newer, larger (>500W), more efficient panels including BIFI

2 FUTURE OF PV AUTOMATED MAINTENANCE

A complete review of the state of the photovoltaics industry, even just the EU-zone PV industry, is beyond the scope of the current article. It is worth however placing commonly known (or author opinion) summary of the current situation on a time-line that shall serve as the narrative structure useful throughout this work.

Much of the economics of PV depends on the cost of electricity (CoE) on the European market, which is in turn driven by demand and variable cost of non-renewable sources. Currently - and in the foreseeable short-term future, mostly due to a drop in demand, the CoE is dropping, but is due for a rebound after current stimulus measures are given time to make their effects shown by a return to growth. The demand for maintenance of PV plants in Europe is rising due to ageing stock, and is due for an acceleration in the mid-long future horizon when infrastructure investment funds, electricity demand and renewable penetration targets become effective. The robotics industry (supported by research institutions) already provides mature (TRL 5-10) technology for inspection drones and cleaning robots, which can however benefit from further refinement (as argued below). Repair robots are more complex, require more power and autonomy, and are therefore to be foreseen entering the market in force after a decade or so.

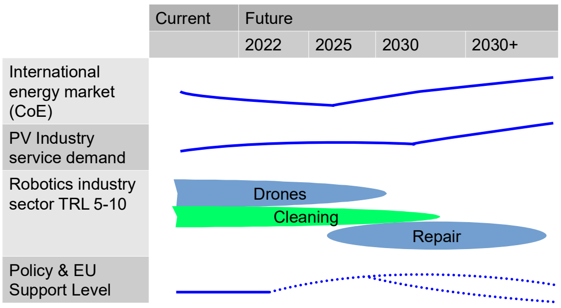

Figure 1: Short-, medium and long-term trends in electricity market, O&M demand in the PV industry, relevant robot categories at technological maturity and EU-wide subsidy and R&D support policy.

The major uncertainty is the EU support level and accompanying policies expected toward 2030. Despite aggressive EU-wide targets for PV (and renewables in general) penetration in that time frame, much depends on increased strong support, accelerated or diminished support in the next decade of EU funding (esp. R&D seen as driver of development). It is for this reason that the article tries to identify key areas for R&D investment, limiting itself to automation in PV plant maintenance.

3 MAINTENANCE STRATEGIES

In the case of cleaning, the strategy required is quite clear - clean at regular intervals determined by the local environment or after a major event (such as a dust-storm).

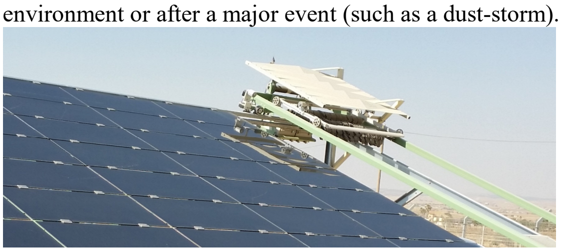

Figure 2. Existing robotic technology example: panel-mounted units for cleaning. Operates automatically after sunset when the inverters are turned off.

The benefits of cleaning as a regular feature of O&M are also quite clear - improved yield and a higher performance ratio to start.

In the case of replacement of defective or non-performing units, the optimal strategy to be employed is somewhat less clear. To begin with, the degradation process of PV installation has multiple physical causes [7], each with its own temporal development and dependence (or lack thereof) on the prior state of the panel.

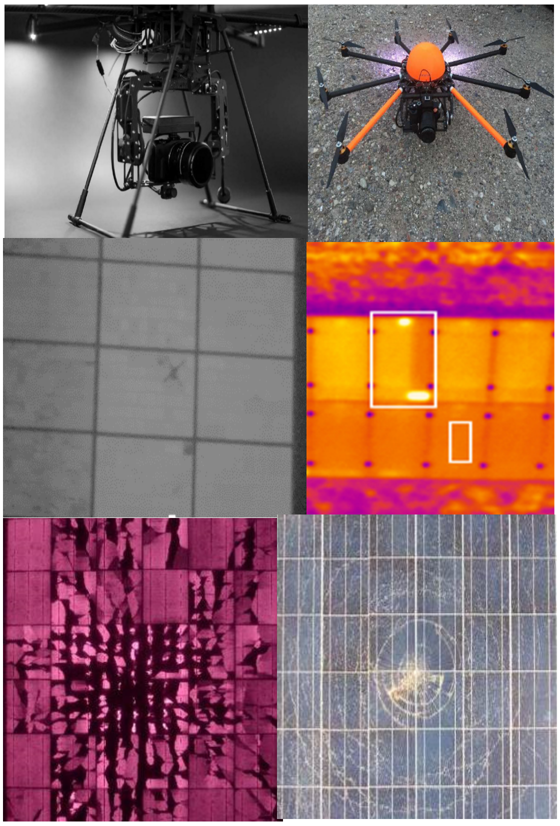

Figure 3. Top: examples of inspection drones [8]. Bottom: images of different degradation modes from different sensors (electro-luminescence, infrared, UV, visible).

A composite distribution of % decreases in PR has been described [8], however sample size, location, basic technological make-up of the installation induces uncertainties in the estimation of this distribution as a predictor for long term PR decreases in PV plants in general. There is still an open research question, yet unclear, as to how many major failure modes such a distribution should entail (unimodal, bimodal, etc.). For the purposes of this paper we chose a (unimodal) gamma distribution (parameters: shape parameter 3, scale parameter 0.0027). We ignore some potentially important factors such as the percentage of defective panels upon delivery - this depends on manufacturer, transport, on-site quality control, which are highly variable. We simply assume regular cleaning is performed and that there the number of malfunctioning units at installation time is negligible.

What we can see, if we perform a stochastic simulation of a hypothetical plant, is that at mean 0.8% degradation, the expected performance ratio of the plant, normalized to that in the first year, is below 80% at 35 years, and that furthermore the variance in individual panel performance increases with time (see Section 6). Both of these trends are nearly (but not quite) linear. The reason for the choice of 80% and 35 years of age of installation is not arbitrary: it is one of the SET goals set out less than a decade ago. According to our best estimation this goal is not yet met by current technology *absent* active maintenance (inspection, replacement and repair). The SET goals are a result of a political process - mediating between societal preferences for energy production and market forces. The case for active maintenance can be made, we believe, on the basis of market economics alone. Before going into the SET goals in more detail, we present state-of-the-art and future robotic technology.

4 ROBOTIC TECHNOLOGY: OUTLOOK

Whereas robots seem ubiquitous, that only holds for the popular imagination and in toy catalogues: industrial robots are actually quite rare, expensive devices. Service robots are conceptual prototypes. The house cleaning robots (a product of MIT's Media Lab) that one finds at the local shopping mall are quite simple, low power and low autonomy machines. Drones are much more common (in industry as well as retail) but only a small fraction of these can be considered *robotic* devices: for safety reasons (and to protect the investment) they are remotely piloted by a human rather than self-steering. The regular geometry of a PV plant (recognizable from mounted cameras) actually make it perfect testing ground for automatically piloted drones. A wider review of robotic technologies can be found elsewhere - it is merely a statement of common fact that affordable, autonomous, high power robots in industrial environments are uncommon, still representing a future concept rather than everyday reality.

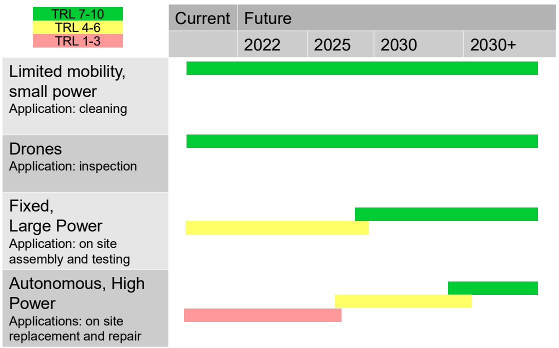

Figure 4. Technology readiness level (TRL) levels of robotic technology, current and forecast.

As mentioned, cleaning robots and drones are already high TRL. Nevertheless they stand to benefit from further improvements. For example: cleaning robots can improve in mounting time and overall cost. Drones may progress toward larger integrated multi-sensor units - at the moment a service team is deployed out carrying multiple, separate sensor platforms, though it may mean higher payloads. Another current drone challenge is limited flight duration, which may be extended with higher energy / power density drive-trains, in other words increased autonomy.

As mentioned, fixed large power robots (industrial robots) are rare, heavy and very expensive. Lighter, cheaper variants of this robots (for on-site assembly and component testing on delivery) should become available before they can be applied in PV plants. Autonomous, high power robots are research-only devices which are not only prohibitively expensive (at sizes needed to handle panels without breaking them) but also, importantly, quite dangerous (more than fixed robots, already subject to extensive regulations and controls). They require quite a lot of R&D before they can be sent out in the field and do autonomous repair and replacement.

5 "SET" GOALS IN PV PLANT O&M

The SET Implementation plan [11] does not only pertain to renewables, much less to photovoltaics. It contains general specifications what the EU energy market should look like in the future. For example, it states that PV should contribute 15% of total EU electricity demand by 2030. This is uncertain, because of the aforementioned market forces that are strong enough to forestall new investment in energy production because of demand uncertainty. Expansion of PV-based energy production is an important unknown with a heavy influence of all other sub-goals.

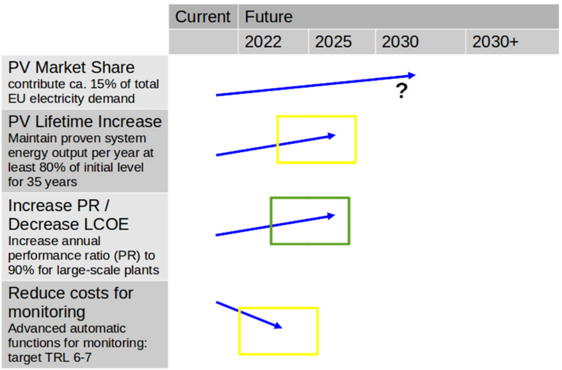

Figure 5. SET (https://setis.ec.europa.eu) roadmap goals pertaining to O&M activities in PV. Increasing EU market share of PV by 2030 requires in part further lowering of O&M costs. Requirements of 80% output at 35 years (0.65%/year) are possible but require maintenance (see Section 6) Legend, boxes: YELLOW (possible, requires effort), GREEN: achievable.

One such sub-goal, already mentioned is to maintain proven system output per year at at least 80% of the initial level for 35 years. This is, effectively, a performance ratio (PR) normalized to that in the first year. We have mentioned that this is not an easily achievable goal without maintenance. More on this topic in 'Smart Maintenance' below. A related goal is to increase annual performance ratio to 90% for large-scale plants. This is already being achieved with new basic module designs and BIFI, so it appears in Figure 5 as 'green'. Finally, one set aim is to reduce monitoring costs by implementing automatic functions for monitoring. This goal is difficult to achieve, because adding sensors and communications increases cost. This is why drones are such an attractive idea: they provide monitoring *without* an increase in sensors and cost that is strongly linear with the plant size.

6 SMART MAINTENANCE

The SET PV related goals are not limited to O&M and market share. They also have to do with performance ratio and the basic technology of electrical conversion. Yet, such increases are subject to limitations. First, new panel design impact would require the replacement of the entire PV stock, which must happen in due time, but not for plants at early and mid-life-cycle. Second, the magnitude of such improvements are limited (on the order of 5%). This is more or less the efficiency increase afforded by regular cleaning (which may range to 10% for dusty environments or less than that for wet, green areas). If we attempt to stochastically simulate NPR, the normalized performance ratio (normalized to the performance ratio at year 0 of operation), based on an approximated probabilistic model of yield decrease (see Section 3), we observe losses at about 8% for the first decades, and more than 25% at 35 years. Yet, with a simple strategy of replacing the least performing 5% of panels at year 10, the least performing 10% at years 20 and 30, the NPR is above 80% at 35 years - reaching the SET target.

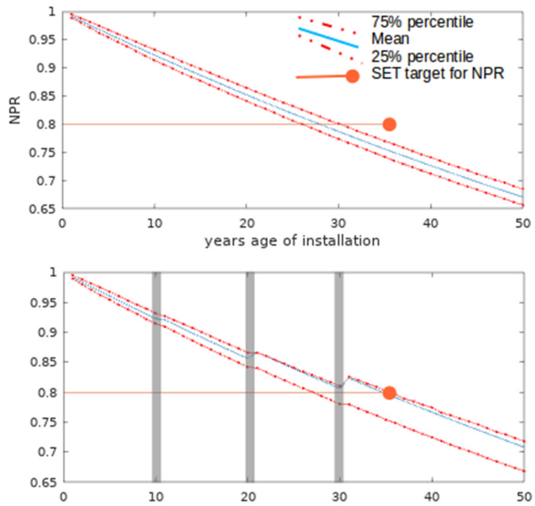

Figure 6. Degradation of panels and its probability distribution (simulated) under (TOP) no intervention and (BOTTOM) under inspection and replacement (panel culling) at decade intervals.

In fact, it seems that regular (every decade) culling of bad panels can provide effective lifetimes of PV plants even to 50 years. The exact economics of this process, when to cull, how much (from 0 to 100%), is to be studied in greater detail and experimentally confirmed. Yet, grosso modo, cleaning and culling each afford ca. 5% output at moderate operational costs - about as much as wholesale replacement of panels to newer technology!

7 MATCHING NEEDS AND TECHNOLOGY

Robotics is not, historically, an eminently market-driven technology, although notable exceptions abound: inspection robots, explosive disposal, welding and painting in assembly lines. In the case of PV O&M, we are not recommending robots for tasks humans cannot do precisely enough, fast enough, are not strong enough for or should not do. Cleaning, inspecting, replacing PV panels are tasks that humans can do - and in places where the labor market permits, regularly perform. We are simply of the opinion - which can be checked on a back of the envelope calculation- , that in Europe currently and globally in the near future, given the sheer size of the repetitive tasks necessary for regular maintenance of an expanded PV market share, it is not practical to assign them to humans. This does not mean elimination of jobs. Certainly drones and cleaning robots involve skilled human operators, therefore allowing co-evolution of skilled jobs and automation. Robots themselves must be maintained and operated. However, whatever robots are developed to do the job, including those not yet available, will be subject to stringent economics, so expanded automation in this context is not a given.

8 SUMMARY

We argue that only an aggressive expansion of existing market solutions, barring the resolution of stark technological challenges at lower TRL ranges, can realistically meet most of the SET roadmap over the 5-10 year horizon by extending and refining existing technologies (drones and cleaning robots). SET targets on maintaining PR over life-cycle especially benefit from improved diagnostics (drones) and regular replacement/repair of defect units (including action by high-powered robots). SET goals require robotic technology improvement in the next 5 years, refining existing technologies, while high-power mechanical units are expected to take longer (2030) rather than medium-term. The overall impact would be improving overall competitiveness and PV market share by reducing O&M costs (the 'other half' of the PV cost). Basic PV technology itself is due to develop in the meantime toward higher yield/ cost of unit leading to a higher combined LCOE reduction. Much however depends on overall energy demand, and whether it will rise vigorously or stagnate past 2022/2025.

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