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Solar power systems for polar instrumentation: why night consumption matters

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Abstract. Autonomous instruments, powered using solar panels and batteries, are a vital tool for long-term scientific observation of the polar regions. However, winter conditions, with low temperatures and prolonged lack of sunlight, make power system design for these regions uniquely challenging. Minimising winter power consumption is vital to successful operation, but power consumption data supplied by equipment manufacturers can be confusing or misleading. We measured the night consumption (power consumption in the absence of sunlight) of 16 commercially available solar regulators and compared the results to the manufacturers' reported values. We developed a simple model to predict the maximum depth of discharge of a battery bank, for given values of regulator and instrument power consumption, solar panel size, location, and battery capacity. We use this model to suggest the minimum battery capacity required to continuously power a typical scientific installation in a polar environment, consisting of a single data logger (12mW power consumption) powered by a 12V battery bank and 20W solar panel, for eight different models of solar regulator. Most of the tested solar regulators consumed power at or below the manufacturer's reported values, although two significantly exceeded them. For our modelled scenario, our results suggest that the mass of the battery required may be reduced by a factor of 26x by exchanging a solar regulator with high night consumption for a more efficient model. These results demonstrate that a good choice of solar regulator can significantly increase the chances of successful year-round data collection from a polar environment, eases deployment and reduces costs.

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1. Introduction

Autonomous instruments deployed in the polar regions are often powered by solar panels and batteries (e.g. Kadokura and others, 2008; Zandomeneghi and others, 2010; Citterio, 2011; Eckstaller and others, 2022). A typical system (e.g. Zandomeneghi and others, 2010) consists of one or more solar panels, a solar regulator, a battery of calculated capacity (often 12 V lead acid), and the instrument itself. The battery may be a single unit or a battery bank consisting of multiple units connected together. A key challenge is powering the instrument during the polar winter, when there is no sunlight and the system may be exposed to temperatures below 0 °C, and so systems are designed to store energy in the battery during the summer months and then operate solely on this stored energy through the winter darkness. The power consumption of the instrument and its ancillaries versus the anticipated environmental conditions thus defines the required battery capacity. It is highly desirable to reduce this capacity, since lower-capacity batteries are physically smaller, cheaper, lighter, easier to transport, and safer to work with in the field.

Lead-acid batteries are considered here as they are commonly used for polar deployments (McGovern and Geller, 2022). Rechargeable lithium-based batteries are damaged by being recharged at temperatures below freezing (Bommier et al., 2020), and so are rarely suitable for use in a solar powered system in a cold environment. Whilst some specialist lithium rechargeable batteries are now available that use internal electronics and heaters to overcome this limitation, they are considerably more expensive than equivalent lead-acid types. Relion's 12V 100Ah low-temperature lithium battery, which is rated down to -20C, has a list price of USD $949 (Dec 2024, approx.€900), which is around 3x the price of a lead-acid battery of the same capacity #crossref below (Lithium Battery for Low Temperature Charging | RELiON, 2024). Whilst calculating the power consumption of the instrument is theoretically straightforward, the power consumption of the power system itself is often overlooked, particularly that of the solar regulator and any other ancillary electronics that are powered continuously (such as low-voltage disconnect circuits). Here we show how neglecting to consider this issue can seriously hamper system performance and lead to instrument failure during the winter.

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1.1. Battery management

Battery capacity depends both on load current and on temperature (Spiers, 2012). Datasheets for batteries commonly quote performance at 25°C (or 80°F = 26.6°C) and for a 20-hour discharge period. For example, a 20Ah battery is specified to produce 1A for 20 hours at 25°C. Reducing load current will increase capacity and increasing it will reduce capacity. This provides a further reason to reduce the power consumption of instruments and associated electronics, as it will increase the available battery capacity. Low temperatures also have a significant effect on battery capacity. At sufficiently low temperatures, the battery electrolyte will freeze at a point dependent on the battery's state of charge. A fully-charged battery will freeze at -50°C, whereas one at 20% charge could freeze at -10°C (Labouret and Villoz, 2010; Spiers, 2012). At -20°C, the minimum charge state required to prevent freezing is 40%. Freezing risks damaging the battery casing and may severely hamper its performance, even after the battery has thawed. The power system design should try to keep the battery sufficiently charged during the winter months to minimise the risk of freezing. Battery manufacturers provide temperature-derating curves for their batteries (Power-Sonic Corp., 2018; Surette Battery Company Ltd, 2020), which show how the available battery capacity is reduced by the need to retain charge in the battery to prevent freezing.

To protect the battery from being discharged too deeply and being at risk of freezing, we recommend the use of a low-voltage disconnect (LVD) circuit. This will switch off the load if the battery voltage falls below a threshold value. It will reconnect the load when the battery recharges above a second, higher, threshold voltage. LVD circuits are built into some regulators (see Table 2) and are useful if the load's power consumption is significantly higher than that of the regulator itself. Standalone LVD units are also available, but if these are used then the standby current of the LVD must also be factored into the overall system night consumption. On some units the LVD thresholds can be programmed by the user, and the threshold values should be configured carefully based on the battery type and expected temperature conditions.

1.2. Solar regulators

Solar regulators are connected between the solar panels and the battery and perform two functions. Firstly, they prevent current from the battery bank from leaking back into the solar panel during the night and being wasted as heat. The majority of regulators incorporate this functionality in their internal electronics, but some (e.g SES-Flexcharge models) require an external blocking diode. Secondly, they ensure that the battery is charged in a safe and efficient manner, often by using a multi-step

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charging regime. A typical multi-step charging regime alters the voltage and current supplied to the battery to ensure a rapid charge to around 80% of capacity ("bulk"), followed by a slower charge to 100% ("absorption"), then followed by maintenance at 100% ("float"). A further "equalization" cycle then occurs periodically to prevent acid stratification and sulfate buildup inside the battery (Morningstar Corp., 2022). Some manufacturers (e.g. SES-Flexcharge) implement their own proprietary charging regimes which may vary from that described here. Charging regimes may incorporate temperature compensation to improve performance, and may be customized to match the battery manufacturer's recommendations.

There are two common architectures for solar regulators: Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT) (Labouret and Villoz, 2010). PWM regulators are an older design and usually cheaper than MPPT regulators. In a PWM regulator, an electronic switch is pulsed on and off rapidly to regulate the average output voltage. The longer the switch is on during each cycle, the higher the output voltage used to charge the battery. The SES-Flexcharge regulators use a low-speed variant of this design where the switch is turned on and off in response to changes in battery voltage (over a period of minutes), which they claim helps to reduce electromagnetic interference (SES Flexcharge, 2012). MPPT regulators (Bose et al., 1985) are a more complex design and claim to be more effective at extracting power from the solar panels (Labouret and Villoz, 2010; Sunforge LLC, 2021). In an MPPT regulator, a switch-mode power converter is used to allow the solar panel and battery to operate at different voltages, whereas in the PWM type the solar panel voltage is always regulated down to match the optimum voltage for charging the battery. Since the solar panel voltage usually needs to be different from the battery voltage in order to extract the maximum power from the solar panel, the MPPT design allows the panel to operate more efficiently (Labouret and Villoz, 2010). MPPT regulators are slightly more expensive, and the switch-mode power converter makes them more prone to emitting electromagnetic interference which may be relevant in applications involving sensitive radio-frequency instrumentation (Ohba et al., 2014).

1.3. Night consumption

The solar regulator itself requires some power to operate, and this is described by the manufacturers as "self-consumption", "own consumption", "parasitic current", "operating consumption" or "quiescent current". The term "self-consumption" may lead to a mistaken belief that this power is deducted from the output of the solar panel, but in nearly all regulator designs, it is consumed from the battery. Some controllers consume more current when the sun is shining, but there is almost always a

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baseline power consumption that is being drawn from the battery at all times. This we refer to as "night consumption". Historically, MPPT regulators had higher night consumption than the equivalent PWM type (Labouret and Villoz, 2010), but we show that the newest designs have night consumptions comparable to or lower than many PWM models. Understanding the predicted night consumption of the chosen system is critical for planning long-term instrument deployment in locations with limited solar input. This study aims to quantify the night consumption of a range of solar regulators, and to provide a calculating tool to enable optimized power system design for autonomous instrument deployment through the polar night.

2. Methods

2.1. Laboratory tests on solar regulators

We tested 16 different models of solar regulator under laboratory conditions to determine if their measured night consumption agreed with the figures quoted on their datasheets. The experimental set-up consisted of connecting the regulator's battery terminals to a 12V lead-acid battery via a dual-channel multimeter (Mooshimeter, Mooshim Engineering), which could simultaneously measure both the voltage and the current consumed. The solar panel input to the regulator under test was left unconnected, representing total darkness. The power consumed in the tests was compared to that specified by the manufacturers.

2.2. Modelling system performance

To illustrate the effect of the solar regulator's power consumption, we devised a simple spreadsheet model for the performance of a solar power system deployed in a polar environment (i.e. locations inside the Arctic/Antarctic Circles). Given the latitude and longitude of the deployment site, the model uses NOAA's Sun Calculator spreadsheet (Solar Calculator - NOAA Global Monitoring Laboratory, 2024), to determine the number of minutes of daylight for each day of the year. For each day, the model calculates the energy input from the solar panels, and then subtracts the energy consumption of both the example instrument and the solar regulator to give a net energy change per day. This net energy change then updates the energy stored in the battery from the previous day, to give a new end-of-day battery state of charge. The model calculates this for every day in a year starting from the deployment date, and finds the lowest value of the end-of-day battery state-of-charge. This is converted to depth of discharge (DoD) – 0% state-of-charge = 100% depth of discharge. This value is the model output – if

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the value exceeds 100%, the system will fail because the battery will run out of energy. To provide a safety margin and to give good battery longevity over multiple seasons, we recommend that this value not be allowed to exceed 60% DoD (i.e. the battery never drops below 40% state-of-charge).

We then used the model to calculate the performance of an example deployment, and varied the power consumption of the solar regulator to show how choosing different models of regulator will affect the system design. The night consumption of each regulator is taken from our experimental results, whilst datasheet values are used for the daytime consumption. For each of the regulators modelled, we determined the minimum battery size (to the nearest 0.5 amp-hour) required to operate the system with the battery state of charge remaining at > 40% at the end of any single day (=60% depth of discharge (DoD).

To estimate the mass and cost of the different batteries required, we took details of 22 different models of sealed lead-acid batteries for cyclic applications from the manufacturer Yuasa (the NP, NPC and REC ranges) and compared battery mass and retail price with the advertised capacity. To give the approximate mass and cost of a battery of given capacity, we interpolated between the known values from the Yuasa batteries.

The example deployment modelled is:

- **Deployment date = 1st January 2024.**
- **Location** = **70 degrees S, 0 degrees E.** An Antarctic location was chosen so that the example deployment year lines up with the calendar year, with deployment taking place in the middle of the summer.
- **Instrument current consumption = 1mA.** We took a common model of datalogger as our benchmark instrument: a Campbell CR1000X consumes around 1mA when powered from 12V and used on a 1Hz scan (Campbell Scientific, 2021).
- **Solar panel nominal output = 20W.** We chose a small solar panel with 20W peak output.
- **System voltage = 12V.** We chose a typical lead-acid battery with a nominal voltage of 12V. In practice the battery voltage will vary between 11.5V and 14.9V depending on circumstances (Morningstar Corp., 2022).

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The model uses the following parameters and assumptions:

- **Solar panel yield = 10%**. We assume that the solar panel produces an average yield of 10% of its rated peak output during daylight hours. This value is a conservative estimate, using an installation at Showa station at 70 degrees South in Antarctica as a best-case scenario (Frimannslund et al., 2021; Tin et al., 2010). This system has a specific yield of 800kWh/kWp/year, which was converted to average yield (joules per second of daylight per watt-peak of installed panel capacity), using the NOAA Sun Calculator (Solar Calculator - NOAA Global Monitoring Laboratory, 2024) to determine the total annual daylight at Showa, resulting in an average yield of 17.9%. To account for the large-scale installation at Showa being highly optimized for yield, and to acknowledge that most small-scale installations will be lower-yielding as a result of non-optimal installation, local weather conditions, cloud cover and panel degradation, we chose a figure of 10% average yield for the model.
- **Starting battery capacity = 50%**. Whilst lead-acid batteries are charged before they leave the factory, they experience a self-discharge of around 1% per month (Surette Battery Company Ltd, 2020). It is not always practical to charge batteries immediately before a field deployment. A 50% starting capacity corresponds to a battery that is installed two years after manufacture, reflecting lead times in procurement, logistics and installation.
- **Low-temperature battery capacity reduction factor = 50%.** Battery manufacturers recommend a variety of de-rate factors for low temperatures depending on the exact battery chemistry and the power consumption of the load (Power-Sonic Corp., 2018; Surette Battery Company Ltd, 2020). However, 50% is a typical value for temperatures of -20ºC. Therefore, a battery sold as 100Ah at 25ºC is considered by the model to have 50Ah of capacity in a polar environment (based on operating at -20ºC).
- **Maximum depth of discharge = 60%.** There is a tradeoff between depth of discharge and cycle life – the number of times that the battery is fully charged and then discharged below a threshold level - often 60% DoD - in the battery's lifetime. For off-grid solar power installations outside the polar regions the battery may experience one cycle per day, so battery manufacturers recommend limiting depth of discharge to 50% to maximize cycle life (Surette Battery Company Ltd, 2020). However, for a polar installation the battery experiences one deep cycle per year, so maximizing

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cycle life is much less important, as even at higher DoDs the cycle life is measured in thousands of cycles. We chose 60% DoD as our threshold value.

- **Charge efficiency = 85%.** We model the battery using a simple coulomb-count model (Ng et al., 2009). The charge efficiency parameter models how much of the energy delivered to the battery during charging is output during discharge. The figure of 85% on average is quoted by (Stevens and Corey, 1996). We do not model the variation of charge efficiency based on battery state of charge, but this could be included in future work.

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3. Results

3.1. Battery mass and price models

Figure 1 shows the relationship between battery capacity and mass, whilst Figure 2 shows the relationship between battery
180 capacity and price. Both vary linearly with battery capacity.

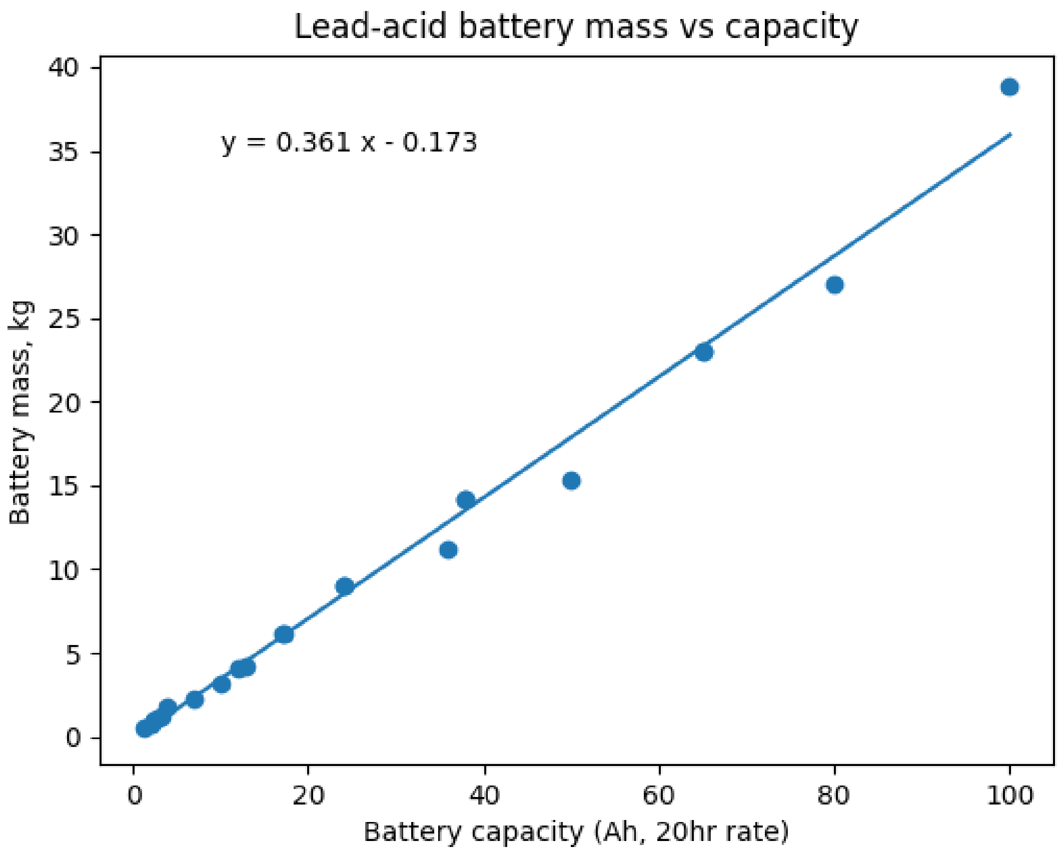

Figure 1 - linear relationship between battery capacity and mass for Yuasa lead-acid batteries

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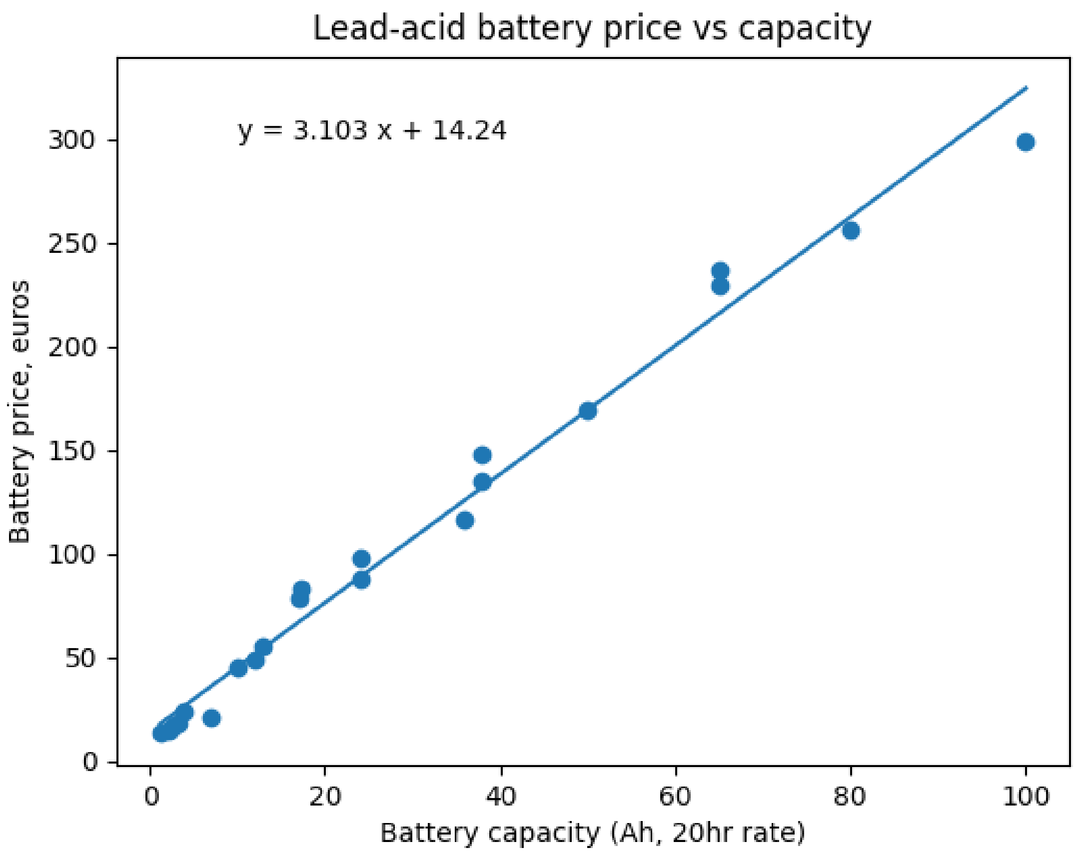

Figure 2 - linear relationship between battery capacity and price for Yuasa lead-acid batteries

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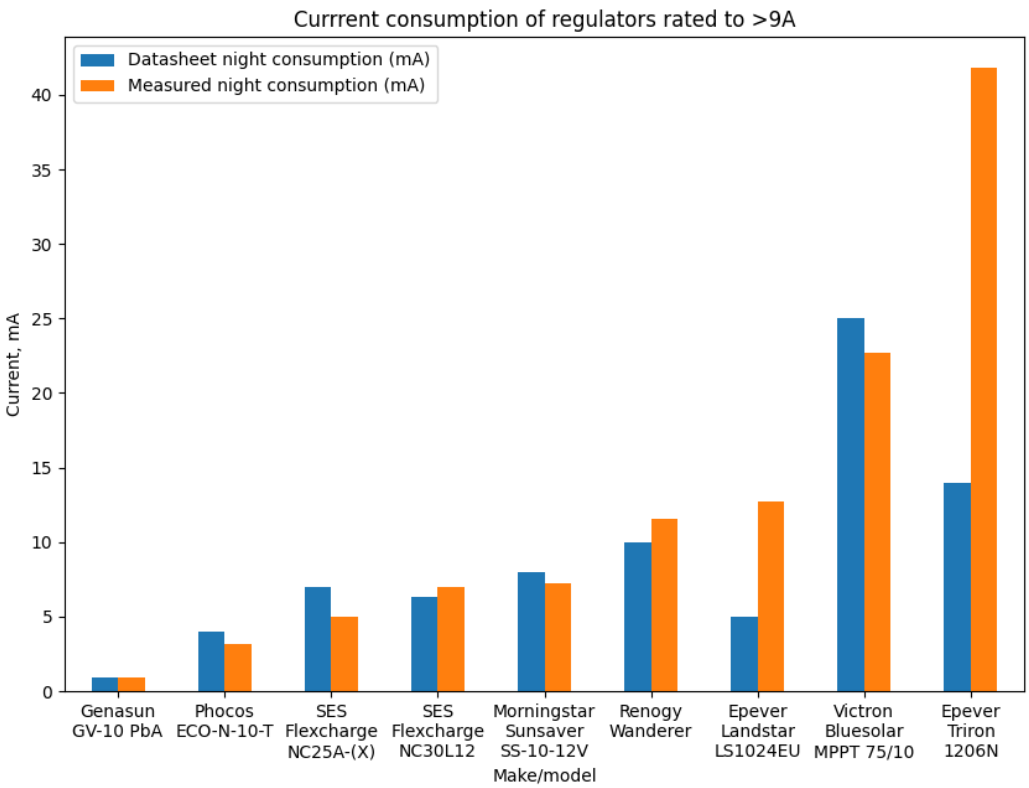
3.2. Solar regulator laboratory tests

The datasheet and measured night consumption values of the regulators are presented in Figure 3-5 (grouped according to current) and in Table 1.



190 **Figure 3 - current consumption of regulators with panel currents rated to 9A or greater. The NC25A(X) is rated to 25A and the NC30L12 is rated to 30A. The other regulators are rated to 10A.**

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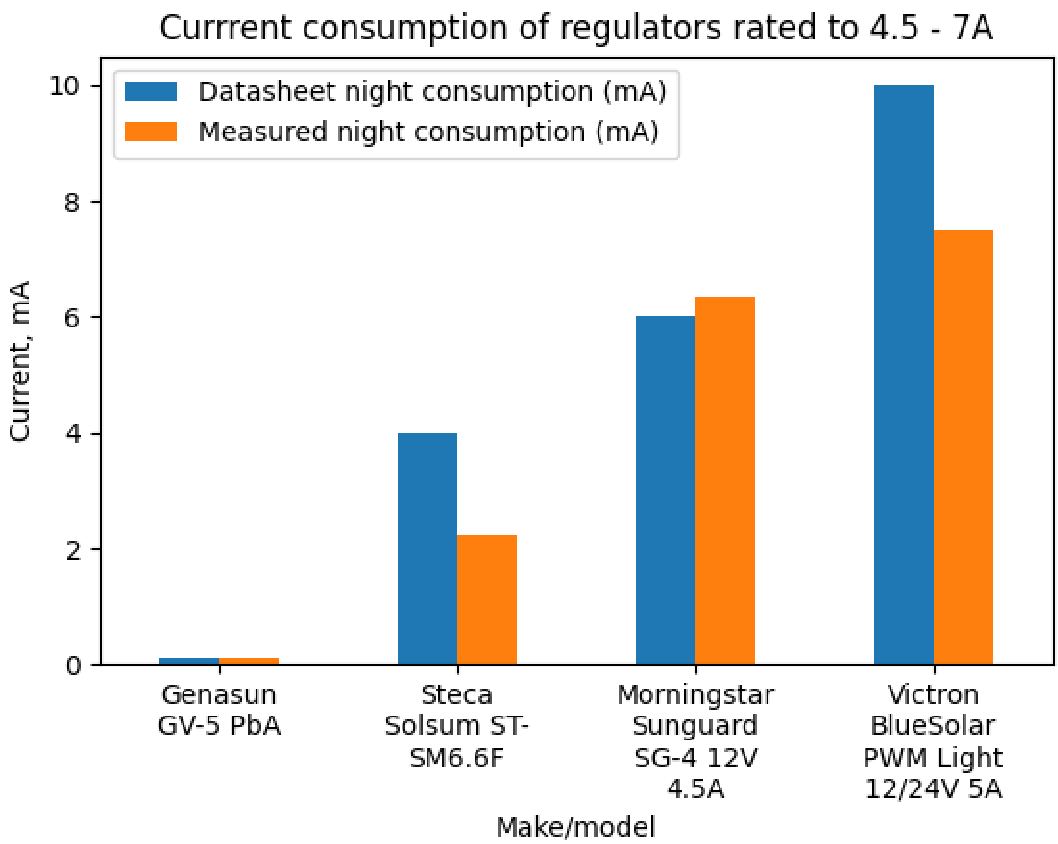

Figure 4 - current consumption of regulators rated between 4.5 and 7A. (GV-5: 5A; STSM6.6F: 6A; SG-4: 4.5A; BlueSolar: 5A)

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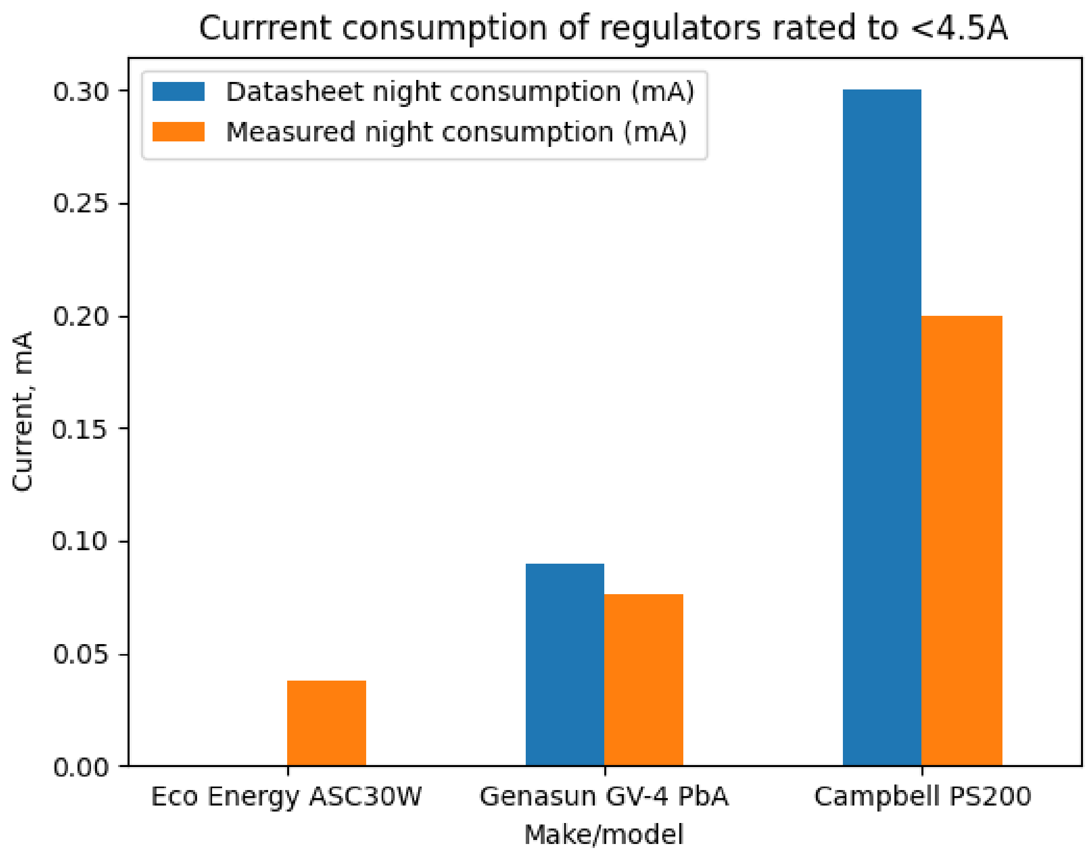

Figure 5 - current consumption of regulators rated to <4.5A. (ASC30W: 2.5A; GV-4: 4A; PS200: 3.6A). Note that the ASC30W has a datasheet current consumption of 0mA.

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Table 1: Manufacturer's specifications and approximate 2023 purchase prices for all regulators tested in this study, alongside measured night consumption when attached to a 12.5V battery.

Manufacturer	Model number	Type	Low Voltage Disconnect built-in?	Approx price (EUR)	Rated solar panel current (A)	Datasheet night consumption (mA)	Measured night consumption (mA)
Campbell	PS200	PWM	No	460	3.6	0.3	0.2
Eco Energy	ASC30W	PWM	No	72	2.5	0	0.04
Genasun	GV-4 PbA	MPPT	No	77	4	0.09	0.08
Genasun	GV-5 PbA	MPPT	Yes	90	5	0.125	0.11
Genasun	GV-10 PbA	MPPT	No	115	10.5	0.9	0.94
Steca	Solsum ST-SM6.6F	PWM	Yes	31	6	4	2.23
Phocos	ECO-N-10-T	PWM	Yes	66	10	4	3.16
SES Flexcharge	NC25A-(X)	PWM	No	137	25	7	5.00
Morningstar	Sunguard SG-4 12V 4.5A	PWM	No	50	4.5	6	6.34
SES Flexcharge	NC30L12	PWM	Yes	215	30	6.3	7.00

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Morningstar	Sunsaver SS-10-12V	PWM	No, but sister model SS-10L-12V does	80	10	8	7.26
Victron	BlueSolar PWM Light 12/24V 5A	PWM	Yes	30	5	10	7.50
Renogy	Wanderer	PWM	Yes	23	10	<10	11.52
Epever	Landstar LS1024EU	PWM	Yes	23	10	5	12.70
Victron	Bluesolar MPPT 75/10	MPPT	Yes	66	10	25	22.68
Epever	Triron 1206N	MPPT	Yes	96	10	14	41.81

Table 1 demonstrates that the majority of the regulators tested met the specifications stated by the manufacturers' datasheets. Some manufacturers (SES Flexcharge and Epever) quote several different power consumptions for different parts of the circuit which then must be totalled up to give the night consumption. The measurements predominantly demonstrate that the night consumption was below the manufacturer's estimates (Fig. 4 and 5), but there were four units with excessive consumption (Fig. 3).

Some models performed better than expected, notably the Steca Solsum ST-SM6.6F, where manufacturer night consumption was 4 mA but measured consumption was 2.3 mA. Campbell PS200 (0.3 vs 0.2 mA), Phocos (4 vs. 3.16 mA), SES Flexcharge (7 vs. 6.3 mA) and Victron Bluesolar (PWM 10 vs. 7.5 mA, MPPT 25 vs. 22.68 mA) also performed better than advertised.

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However, the two Epever regulators both had measured performance that was far worse than their datasheet claimed (Landstar 5 vs. 12.70 mA and Triron 14 vs. 41.81 mA). The Renogy performed slightly worse than specified (<10mA vs 11.5mA). It is worth comparing these figures with the 1mA load current for our example Campbell datalogger: for the Eco Energy ASC30W, the current consumption of the regulator is 4% of the load current. By contrast, the Victron Bluesolar MPPT75/10 has a night current of almost 23x that of the load – which would result in 96% of the system's power consumption going into running the solar regulator.

Table 2: Modelled battery sizes and masses required to maintain >40% battery capacity (<60% DOD) for one year with a selection of solar regulators tested in this study. Battery masses and prices are estimated using Yuasa battery data in Figures 1 and 2. Calculations are based on a scenario where an instrument consuming 1mA is deployed on the 1st of January at 70° S with a 20W solar panel and 12.5V battery.

Manufacturer	Model	Minimum battery size required from model (Ah)	Estimated battery mass (kg)	Estimated battery price (Euro)
Genasun	GV-4	5	1.7	30
Genasun	GV-5	5	1.7	30
Eco Energy	ASC30W	5	1.7	30
Campbell	PS200	6	2	33
Steca	Solsum ST-SM6.6F	14.5	5.1	59
Phocos	ECO-N-10-T	21	7.4	80
Morningstar	Sunguard SG-4	33.5	11.9	119
Victron	Bluesolar MPPT 75/10	125	45	402

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3.3. Model results

Table 2 shows the different battery sizes required to support the power consumption of several of the regulators tested under these hypothetical deployment conditions. Using the Victron Bluesolar MPPT 75/10 would require a battery of at least 125Ah. A battery of this size is over 45kg and costs more than €400. Choosing an alternative regulator with lower power consumption allows for the use of a smaller battery: the inexpensive Steca Solsum ST-SM6.6F needs only a 14.5Ah battery, with a mass of around 5.1kg. The Genasun GV-4, Genasun GV-5 and Eco Energy ASC30W offer the best overall performance, allowing the use of a 5Ah battery, with a mass of <2kg. Choosing one of these best-performing regulators results in a 26x reduction in battery mass and a 13x reduction in battery price when compared with the Victron MPPT 75/10.

4. Design recommendations

Beyond careful choice of solar regulator and modelling of system performance, we also recommend:

- Minimising the power consumption of the instrument itself – such as by powering down sensors between measurements.
- Using a solar regulator with temperature compensation.
- Using an LVD to protect the battery from freezing.
- Choosing LVD thresholds carefully – having a relatively high voltage for the "reconnect load" voltage helps ensure that the battery is well-recovered before it delivers power to the load.
- Using a well-insulated enclosure for the batteries, especially if the electronics is included in the battery box, as the insulation will help retain heat from the electronics.
- Increasing the battery capacity by a "factor of safety". For a system with low power consumption, it may be practical to increase the battery capacity as predicted by our model by 50 or 100% to provide additional resilience. For more power-hungry systems a smaller factor may be used. Consider the number of "days of autonomy" (i.e. how long can the system run on battery power alone) and increase battery capacity based on data about local conditions.
- Increasing the modelled solar panel capacity by a "factor of safety". Solar panel performance can be severely degraded by snow or ice frozen onto the panels, or by shadowing from local topography. Using larger panels (or more, smaller

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panels) can help ensure that the system produces the necessary power during the crucial spring period when the battery levels are at their lowest.

- Mounting the solar panels vertically (to minimise snow retention) and facing toward the Equator. If there is local topography blocking the direct sightline, consider multiple panels facing in different directions (e.g. one facing east and one west).
- Considering that large solar panels can have significant wind loading and need to be appropriately supported. Multiple smaller panels may be easier to manage than one large one.
- Planning for local snow accumulation when choosing the mounting for your panels – they need to be mounted high enough to be out of the snow in the spring.
- Testing the performance of your entire system before deployment, ideally in a cold chamber to ensure that everything performs as expected at polar winter temperatures.

5. Conclusions

When designing a solar-powered autonomous instrument for use in the polar regions, it is vital to consider the power consumption of the whole system, not just the instrument itself. These laboratory tests demonstrate that the power consumption of solar regulators varies significantly, and can differ from that specified by the manufacturer. Careful choice of solar regulator (and any other ancillary electronics) can prevent the equipment from running out of power and damaging the batteries during the polar winter. It can significantly reduce the size and mass of the battery required for a successful deployment, which reduces both purchasing and logistics costs. Power calculations should therefore include the 'night consumption' of the regulator and other ancillaries when designing systems for autonomous operation in the polar regions, particularly over winter. Careful power system design can reduce the cost and complexity of purchasing, deploying and operating instruments and increase the chances of successful, year-round data collection.

Data availability

Data and Python code for the plots in Fig. 1-5 is available via Zenodo https://doi.org/10.5281/zenodo.15114767 or at https://github.com/CHILCardiff/solaregulators-plots

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Code availability

The spreadsheet used for the modelling in this paper is provided in Microsoft Excel and OpenDocument Spreadsheet formats. Instructions for its use are provided within the spreadsheet and in the README.md file. The spreadsheets may be obtained from Zenodo https://doi.org/10.5281/zenodo.15115132 or at https://github.com/CHILCardiff/solarregulators-model.

Author contribution

MPJ conceived the study. MPJ, LC, JH, PC, TN and JP made measurements of solar regulator performance. MPJ and JH developed the spreadsheet tool. All authors contributed to the manuscript. This is Cardiff EARTH CRediT Contribution 44.

Competing interests

The authors declare that they have no conflict of interest.

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